Author:
Warren, Thomas James Benjamin

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An experimental and theoretical study of the feasibility of producing electricity and heat from willow biomass on a small-scale.

An experimental and theoretical study of the feasibility of producing electricity and heat from willow biomass on a small-scale

Thomas James Benjamin Warren

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An experimental and theoretical study of the feasibility of producing electricity and heat from willow biomass on a small-scale

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ABSTRACT

Environmental and economic factors have lead to a search for alternative sources of power; biomass power is one alternative. The low energy density of most biomass fuels may mitigate against large-scale generation plants. Small farm-based or rurally sited units could provide a solution. The practical and theoretical feasibility of these systems must be assessed before application.

An investigation of farm sizes in the UK concluded that a 30-kW electrical (kWe) downdraft gasifier and generator could be used on most farms where biomass power is an option.

An experimental gasifier, based at Long Ashton Research Station, was tested to determine its practical suitability. The gasifier was converted to run on wood chip from short rotation coppice-willow (SRC). The efficiency of the conversion system was measured at 14.9 %. Instabilities in the reactor and a lack of automation in the fuel feed and filtration mean that more modifications will be necessary for an implemetable unit.

The LARS-willow was developed, this uses weather data (measured and calculated) to determine potential yields for SRC for 26 UK sites.

The Biomass Energy Analysis Program (BEAP) was developed to investigate energy balances of biomass systems. The analysis accounted for direct and indirect energy consumption of complete systems i.e. establishment to decommissioning. The BEAP was combined with the LARS-willow model to calculate potential Energy Rates of Return (ERRs) for 26 UK sites, operating a 30-kWe system. Potential ERR values ranged from 15.2 to 27 with yield variations. A risk assessment showed that calculated variations in yield would not diminish the favourableness of the ERR values.

An economic model was developed to calculate potential profitability of a 30-kWe system. This showed that such a system is not profitable now. Analysis of the future economics of power shows that it this is unlikely to change over the medium term.

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The modifications to the 30-kWe gasifier were done in conjunction with R.I. Parfitt of IACR-Long Ashton who also aided in the collection of the readings for pressure and temperature.

The LARS-willow model was modified from a version developed by M. Semenov and L. Evans at IACR-Long Ashton.

All other work within this thesis is that of the authors alone except when referenced.

AUTHORS DECLARATION

I declare that the work in this dissertation was carried out in accordance with the regulations of the University of Bristol. The work is original except where indicated by special reference in the text or mention above. No part of the dissertation has been submitted for any other degree.

Any Views expressed in the dissertation are those of the author and in no way represent those of the University of Bristol.

The dissertation has not been presented to any other University for examination either in the United Kingdom or overseas.

T.J.B. Warren

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CHAPTER 1

INTRODUCTION TO BIOMASS FOR ENERGY

THE NEED FOR ALTERNATIVE SOURCES OF POWER

In the past three decades, considerable effort has been directed towards the investigation of alternative energy sources, primarily nuclear and renewables. Some of the reasons for this are discussed below.

In the last century world population has risen at a rate never seen before, an increase that does not seem to be abating. By 2000, the predicted world population will be more than 6 billion and increasing at a rate of approximately 2% per year (Ehrlich and Ehrlich, 1991). Everybody uses energy in some form; the developed countries use amounts of energy per capita much in excess of that in undeveloped or non-industrialised countries (Leach *et al.*, 1986). This extra energy consumption is used in providing the high 'living standards' of the industrialised world. As non-industrialised countries develop economically and their 'living standards' increase so will their energy consumption. To stop ever increasing quantities of energy being used to support lifestyles in the developed world, more efficient modes of energy consumption must be implemented. This stopgap measure is often considered politically, socially or economically unfashionable, therefore it is safe to say that the consumption of energy in the world is set to rise rapidly in the future.

Since the industrial revolution, fossil fuels have provided the majority of the energy consumed, especially in the developed world. Consequently, the developed world has become highly dependent on these finite fuel sources for basic living. How long they last is dependent on the rate at which they are consumed and the rate at which new reserves can be found. As resources dwindle there will be inevitable economic and social consequences which will not be beneficial to society. There is an obvious need for alternative sources of energy to replace fossil fuels.

Even if fossil fuel resources were unlimited, consumption leads to an increase in CO_2 in the atmosphere. There is little doubt that this increase will lead to a rise in the greenhouse effect (although the consequences of this are debatable). At the Rio Earth Conference, it was decided to reduce carbon dioxide emission levels to 1990 levels by the year 2000 (Grubb *et al.*, 1993). This is going to be difficult if there is the likely increase in energy consumption mentioned earlier. There must be a switch to energy sources that produce less carbon dioxide per unit of power delivered. There are also many other pollutants produced by burning fossil fuels, such as sulphur dioxide, which have detrimental environmental effects, such as acid rain.

There is an obvious need for non-fossil fuel energy sources capable of meeting rising demand. Alternative energy resources come in many forms which can be divided into renewable and non-renewable.

Nuclear energy is the only major non-renewable form. The demise of fast breeder technology has dampened the hopes of nuclear fission producing a significant amount of electricity in the future

Renewable energy sources, in contrast, are geographically widespread since their primary energy, directly or indirectly, is the sun. There are many renewable sources: wind, wave and solar for example. It is highly unlikely that one renewable resource could provide all the energy necessary in a global, or countrywide context (DTI, 1992). Many renewable resources are unpredictable and could not be relied upon to produce power continuously. A successful renewable energy strategy would have to be diverse and have many different technologies working simultaneously to overcome this problem.

If the world is to avoid both drastic energy shortages and environmental catastrophes then renewable energy technologies must be developed to first complement and then replace existing technologies.

BIOMASS

One renewable energy resource which has received considerable attention is biomass and, especially in Europe and North America, the production of electricity from coppice Willow or Poplar. There are several reasons for this interest.

The over production in Europe of food from agricultural land has meant the imposition of set aside grants. If land can be used for non-food crops farmers can supplement their falling revenues. Biomass production is environmentally low impact (ETSU, 1989) and may also prove economically attractive.

In the long term, it would be hard to argue the case for a biomass renewable energy strategy based on current unsustainable agricultural policies. However, these practices, which necessitate the set aside scheme, could in the short term provide a useful, and necessary, starting block for biomass energy production.

Recent figures have suggested that by the year 2025, the UK alone could have a practicable biomass resource (coppice, forest wastes, farm wastes etc.) of 100 Terra Watt Hours per Year ($TWh.y^{-1}$) (DTI, 1992). This makes coppice biomass a useful proposition for the future energy strategy of the UK.

The technology for producing wood fuel is well developed, with years of research into the agronomy of establishment and management and, recently, into highly productive, disease-tolerant clones of willow and poplar. There are new and efficient machines for planting and harvesting (Neale and Reed, 1992; ETSU, 1989). However, until recently, methods for turning such fuel into power have received little attention, other than on a large-scale, for instance fluidised bed gasification. There are several reasons why generating electricity from biomass, on a large-scale, may cause problems. Equally, there are several reasons why it may be beneficial to generate electricity on a smaller scale.

Biomass is a fuel with a low energy density (at 20% efficient conversion 1 tonne ($3.5m^3$) approximately equals one Mega Watt hour (MWh)). As a result large scale centralised production can have transportation problems. The quantity of fuel necessary to run a large generating plant i.e. 2 MW for 90 % of the year at 20% efficiency is approximately 160,000 tonnes. Estimating yield at 12 oven dry tonnes per hectare per year (odt.ha^{-1}.yr^{-1}), would mean the area necessary would be approximately 13,000 hectares (ha), a large quantity of land. This land is unlikely to be owned by one farmer in the UK, so transportation of fuel from a number of farms to the central power station would be necessary. Individual site variables (soil types, water availability, social and planning factors etc.) could mean that some of these farms could be many miles away from the conversion site. This could lead to high energy and money expenditure in transportation.

Independent of the energy usage associated with large-scale transportation there will be social factors. It is inevitable that power stations will usually be within rural areas and it is likely that there will be widespread opposition to heavy transport lorries on rural roads at all hours of the day. Large-scale modern power stations today do not need a large work force so the promise of employment could not be used to placate dissenters. Apart from public opposition to transport, the sighting of a large unsightly installation in a rural area could bring significant planning problems.

The implementation of a large-scale power station also needs a significant capital investment. It is unlikely that anyone will spend this much money without a guaranteed fuel supply. This would mean the signing of long term contracts for wood production (perhaps 20 years). It may be hard to convince farmers to commit large areas of their land to one crop for such a long time to a new, unproven, enterprise.

Consequently a small-scale system that could be placed on a single farm or a co-operative of two or three small adjacent farms, could have a useful role to play in future energy policy.

A SMALL SCALE SCENARIO AND ITS BENEFITS

In contrast to a large-scale system, a small-scale system could be placed on a single farm. This would reduce the energy and monetary expenditure in transport. Small-scale generating plants would face less public opposition for perceived pollution and noise. If the scheme proved uneconomic or a more attractive use for the land came along the investment in machinery (much lower than that of a large-scale power plant) would be easier to write off as a financial loss. The farmer also has the benefits of capitalising on the increased profits available from selling a high added value product such as electricity rather than a low quality product such as wood chip. An investigation, similar to the one undertaken in Warren *et al.*, (1995), but using more recent farm statistics shows the following.

INVESTIGATION OF FARM SIZES AND THE CHOICE OF SIZE FOR A SMALL-SCALE BIOMASS TO ELECTRICITY SYSTEM

Table 1. Farm-size group statistics (Nix, 1996) and potential production figures for the UK.

Characteristic	Size groups (ha)		
	10-50	50-200	> 200
No. of holdings	69100	50800	10400
Total ha	1790000	4920000	3890000
20% of total	358000	984000	788000
MWh potential (assuming 20% conversion efficiency)	3550000	9750000	7710000

The largest group of farms in the UK is in the size grouping 50-200 ha (Table 1). If 20% of a farm's area were to be dedicated to fuel production, this would mean areas of between 10 and 40 ha per farm. At 20 % conversion efficiency, 1 tonne of wood chip can produce approximately 1 MWh electrical (Chapter 4). If a generator operated for 70% of the year and assuming 12 oven dried tonnes per hectare per year ($odt.ha^{-1}yr^{-1}$) these areas would need generators in the range 20 to 80 kWe. A system at the lower end of this range would give maximum market penetration since it could be used on smaller farms, and used in multiples on larger farms. A system however, must not be too small or the capital outlay against income would be too large to be economic.

30-KWE SCENARIO

A 30-kWe system would produce 184 $MWh.yr^{-1}$, and require 222.64 oven dry tonnes (odt). This would require from 12 ha (@18.6 $odt.ha^{-1}yr^{-1}$) to 18 ha (@12.4 $odt.ha^{-1}yr^{-1}$) of coppice. This size of system was chosen as being the most suitable for the small-scale scenario envisaged. A 30-kWe system would be a suitable size for all but the smallest farms in the envisaged farm sector. In multiple units, it would be suitable for larger farms. Selling electricity at 4 pence per unit it could raise almost £7500 a year, a considerable quantity of money.

Table 1 shows, for England and Wales, the distribution of farm numbers against size groups, and the relative areas these cover. The 50 ha to 200 ha size group, most of which could operate 30 kWe units independently, is the most obvious target group. They account for almost half the total hectareage, with a potential of some 10 TWh of electricity. Larger farms have a potential to produce 8 TWh. However, there is also the possibility of the smaller farms operating as co-operatives, or as suppliers to larger farms, with a further potential of 3.5 TWh. Thus, there is a theoretical 21.5 TWh, though it is accepted that not all the available land would be suitable for coppice. If 75% of the farm available were used, they could generate some 16 TWh per year.

NON-FARM USES FOR A SMALL-SCALE BIOMASS-TO-ENERGY UNIT

In addition to farm-based electricity production, small-scale units have other potential uses in rural communities. Production of electricity for small communities is feasible and has the benefit of providing a use for the heat produced in association with the electricity production. Similarly, large rural (or out-of-town) complexes like supermarkets, swimming pools, hotels, and leisure centres etc. could use a small unit for electricity production and use the heat to good effect. In these cases, local farmers could be used to provide the fuel.

CONCLUSION

At present, much is being made of the possibility of using set-aside land for generation of electricity and heat from biomass. However, even without this biomass could have a significant role to play in electricity generation in the future. Unlike wind or wave power, its output can be reliably determined for a substantial period. This 'scheduleability' could lead to a much larger sector of the energy market being devoted to biomass than to more established wind generators. There would be no need for alternative sources of power for periods when the conditions are not correct (winds too high or too low for instance). It could also lead to biomass being used to provide niche electricity markets such as peak lopping and off grid supplies.

The energetics and economics of biomass will determine its practicality for the future. The possible variations in the energy market place in the future will significantly affect the economic practicality of biomass. However, an energetic study can give a measure of feasibility, based on current technology, which will not vary over time.

AIMS, DIVISIONS AND AN INTRODUCTION TO PRESENT THE WORK

The success of biomass is dependent on the mechanical and energy feasibility of biomass-to-energy systems and on the economics of such systems.

The economics of biomass is a complicated subject as are the economics of all alternative, and especially renewable, energy sources. In the UK the hidden subsidies of many years of government investment in established energy sources distorts the energy market. In the future the economics of energy production may become more comparable but they will inevitably become more complicated with the introduction of carbon taxes and other economic devices.

At present, the economic feasibility of a system can be only judged in the short term. This may lead to underdevelopment of what may be a highly useful form of energy production. Using a more deterministic approach to the feasibility of biomass systems could complement economic analysis and provide a good way of determining the suitability of biomass for the future.

The energy feasibility of a small-scale biomass-to-energy system is of little value if the machinery to operate such systems is not available. As well as the theoretical analysis of systems, the development of a suitable small-scale machine is a high priority.

MECHANICAL FEASIBILITY STUDIES

Work on the mechanical feasibility of the systems in question has been limited at Long Ashton Research Station (LARS) to the machinery converting wood to electricity and heat. The feasibility of the production of the biomass fuel has not been part of the current investigation. However, an understanding of methods of management, harvesting etc., leads to the conclusion that there are few problems with the feasibility of producing wood fuel in the quantities required.

To study the feasibility of a small-scale biomass to electricity system and develop a commercial conversion machine, a 30-kWe downdraft gasifier system was installed at LARS. The choice of this type of machine is covered in Chapter 2. Experimentation and modification of 30-kWe system at LARS was carried out to achieve three aims.

1. To determine the efficiency of producing electricity and heat from a small-scale downdraft gasifier.

2. To investigate the stability of the gasification process and whether the gasifier could reliably support electrical generation into the national grid.

3. To investigate the effectiveness and reliability of the overall system.

THEORETICAL FEASIBILITY STUDIES

ENERGY ANALYSIS

Theoretical feasibility can be best investigated using an energy analysis as mentioned earlier. A computer program (Biomass Energy Analysis Program (BEAP), Chapter 6) was developed to implement the methods described in Chapter 5. This program was used to study various systems and scenarios. The analysis had six main aims.

1. To implement the energy analysis in the BEAP program.

2. To validate the BEAP model.

3. To investigate the Energy Rates of Return (ERRs) of the 30-kWe scenario on an UK basis using yield data.

4. To provide a risk assessment based on yield, for a number of locations in the UK.

5. To investigate the sensitivity of the 30-kWe scenario to certain changes in the system.

6. To assess two cases of biomass-to-energy in use or in planning.

ECONOMIC ANALYSIS

The economics of energy production systems are hard to predict accurately in the long term. However, it is necessary to consider these economics when looking at the feasibility of a system. The economics of the 30-kWe scenario was assessed over the proposed lifespan of the scenario. This analysis is a good partner to the more rigorous energy analysis. An economic model of the proposed 30-kWe was developed (Chapter 10).

The nature of economic analysis is such that the results must be seen in the context of the economic market place of the time. To contextualise the results of the economic analysis there is an assessment of the economics of power generation.

The future of the economics of power generation is discussed in Chapter 10 with particular reference to possible future methods that might be used by governments to encourage non-fossil fuel based power generation.

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CHAPTER 2

THEORETICAL BACKGROUND TO THERMAL CONVERSION METHODS FOR SMALL-SCALE ENERGY PRODUCTION FROM BIOMASS

INTRODUCTION

It is necessary to consider the practical feasibility of converting biomass to electricity. This chapter provides the theoretical background for understanding the research and the choice of conversion machine. In the past, most biomass conversion to electricity has been through combustion, to produce steam then electricity utilising steam turbines. However there are problems with this.

At low outputs (below 500 kWe) steam turbine production is not economically viable (Bridgwater and Evans, 1993) and, at this scale, figures for efficiency of less than 20% can be expected (Prasad, 1995). This level of efficiency for steam turbine production is low when the high capital costs of the machinery are considered. If production is based on many small units (20-200 kWe), as in the proposed scenario, then this is a major problem. At these small scales, efficiencies for other thermal conversion methods such as gasification and gas engines are considerably higher (Bridgwater, 1995).

These problems have led to a search for a suitable small-scale conversion system at a cost low enough to facilitate a large take-up. The most viable solution is to use a thermochemical method. Thermochemical conversion involves converting fuel into another, more easily used fuel by treatment with heat.

Small generator sets exist; these are Combined Heat and Power (CHP) units and are suitable for use on a small scale. These units use internal combustion engines and consequently steam cannot be used to drive them. However, thermochemical methods produce liquid or gaseous fuels that can be used to drive internal combustion engines.

THERMOCHEMICAL CONVERSION METHODS

Thermal conversion of biomass has divided into two fields of research, pyrolysis and gasification. There has been some work into liquefaction but this has not been significant. The first two processes are not dissimilar and have some common stages.

PYROLYSIS

Pyrolysis is a chemical process present in all fires. In the presence of heat and the absence of oxygen, wood degrades (Watt, 1979). This produces several gaseous products. Pyrolysis reactors must be heated either by external heating or by passing a hot inert liquid or gas through the bed.

GASIFICATION

In gasification, heat is generated inside the reactor by burning some of the fuel. The process is a mixture of pyrolysis, oxidation and reduction that produces mainly gaseous products (Kaupp and Goss, 1984). These gases are predominantly carbon monoxide and hydrogen with some CO_2 and methane. If air is used to feed the process, there is a large proportion of nitrogen present in the gas.

FUELS PRODUCED BY GASIFICATION AND PYROLYSIS

Nearly all the liquid, gaseous and solid products from the above processes have some value as a fuel although it is not economic to use all of them. When the gases produced by both methods are cooled, they divide into gaseous and liquid products. With both processes, there are also solid products: ash, charcoal and slag.

GASEOUS PRODUCTS

Gaseous products vary with thermochemical conversion method (Table 1). The calorific value of the gas will determine the method in which it is used.

Table 1. Important chemicals produced from different forms of gasification (Grassi et al., 1987)

	Chemicals Present	Processes
High Calorific Value (33-42 MJ/m^3)	CH_4	Hydrogasification
Medium Calorific Value (10-20 MJ/m^3)	$CO + H_2$	Pyrolysis, Steam Reforming, Oxygen Blown Gasifier
Low Calorific Value (2-4 MJ/m^3)	$N_2 + CO + H_2 + CH_4$	Air Blown Gasifier

LIQUID PRODUCTS

The liquid products of both gasification and pyrolysis contain oxygenated organic compounds that have high calorific values. In gasification these compounds are not produced in large enough quantities for their extraction to be economic. Pyrolysis liquor is readily burnt as a fuel and is produced in significant quantities. The presence of water and oxygen in the pyrolysis liquor can lead to handling problems and there are problems with incompatibility with existing fuels (Bridgwater and Evans, 1993). The liquor must be upgraded to produce a suitable fuel, for example synthetic gasoline.

SOLID PRODUCT

The solid fuel produced by both processes has a low ash content. Both processes will produce a significant quantity of charcoal because of unavoidable inefficiencies. This charcoal has a useful calorific value and has some commercial uses as a filtration medium.

CONCLUSION

Since our scenario envisaged an on site system there is no need for the high energy density fuels which liquefaction and pyrolysis produce. The higher costs and technology of these systems are not conducive to a farm-sized facility. The obvious choice is gasification.

GASIFICATION REACTORS

There are several different types of gasification reactor: downdraft, updraft, crossdraft, and fluidised bed.

UPDRAFT

In an updraft gasifier the air flows upwards in the opposite direction to the fuel flow. The gas is drawn off at the top, increasing the efficiency, since much of the heat in the gas is used to dry and preheat the fuel. Therefore, the gas leaving the top is at a low temperature (Kaupp and Goss, 1984). There are significant problems with this. Oil and tar vapours are not removed in the reactor. This means that if the gases are to be used in a situation where they must be free of tar and oil they must be cleaned before use. The removal of oils and tars from a gas flow is a complicated and expensive process. The problem can be relieved by drawing the gas off earlier i.e. just above reduction zone. This decreases the tar content but also decreases the cycle efficiency since the gas is at a higher temperature on exit.

If the gas from the gasifier is to be burned in a boiler immediately after production updraft gasification is an efficient method. However, it does not lend itself to applications such as internal combustion because of the complicated gas cleaning necessary. Therefore, updraft gasifiers are best suited to systems in the 500 kW to 2.5 MW range where gas turbines or steam turbines are used.

DOWNDRAFT

In a downdraft gasifier the air flows downwards, in the same direction as the fuel flow. The air is introduced in a 'hearth' oxidation zone where the combustion takes place. All the tar and oil vapours produced during heating and combustion of the fuel must be made to flow through the combustion zone of the gasifier. The high temperature at this point burns or 'cracks' the tars and thus eliminates some cleaning problems. The effectiveness of the tar and oil removal is determined by several variables, the most important of which is the design of the air inlets (tuyeres) and the geometry of the partial combustion zone (Garcia-Bacaicoa *et al.*, 1994; Kaupp and Goss, 1994).

Downdraft gasification has several problems. The hot gas does not flow over the fuel before oxidation and reduction, as in an updraft gasifier, so the moisture content of the fuel must be kept lower (typically below 20%). The susceptibility of the grate to clog means the fuel must be clean otherwise slag formation can cause problems.

Downdraft gasifiers seem to have no effective lower limit, as they operate efficiently even in very small units. However, there are several doubts on the feasibility of units of more than 200 kW (Williams, 1995; ETSU, 1993).

CROSSDRAFT

Crossdraft gasification was developed to provide a gasifier with short start-up and good load following. The high gas exit temperatures mean considerable cooling is necessary. The high temperatures in the partial reduction zone, 2000 °C and higher, mean that parts of the reactor must be cooled, an added complication (Kaupp and Goss, 1984). It is accepted that crossdraft gasification produces gas that is only of use for heating rather than direct combustion (Bridgwater and Evans, 1993. ETSU, 1993).

FLUIDISED BED

Fluidised bed reactors were developed to provide large generating capacities. They are high technology units and operate in the 2 MW to 50 MW plus range (Bridgwater and Evans, 1993). Consequently, fluidised bed reactors are well above the unit size a single farm could use.

There are several gasifier designs that do not fit into the above categories. Some designs use one method for starting e.g. crossdraft and then switch to another (to give a fast start time but a more manageable gas during the majority of the operation); some are combinations such as crossdraft/updraft.

CONCLUSION

For the envisaged scenario, downdraft gasification is the best option. There are other benefits to downdraft gasification. Downdraft gasifiers produce little tar and the technology for a simple system is rudimentary. This increases the serviceability of the system without the need for specialist help, important if a system is to be popular with farmers. There are several small-scale biomass downdraft gasifiers on the market although none are designed to work in the way envisaged. Most units available at present are designed to work as an off-grid, stand alone unit or have yet to prove themselves as stable systems for generating into the grid.

CHEMISTRY OF DOWNDRAFT GASIFICATION

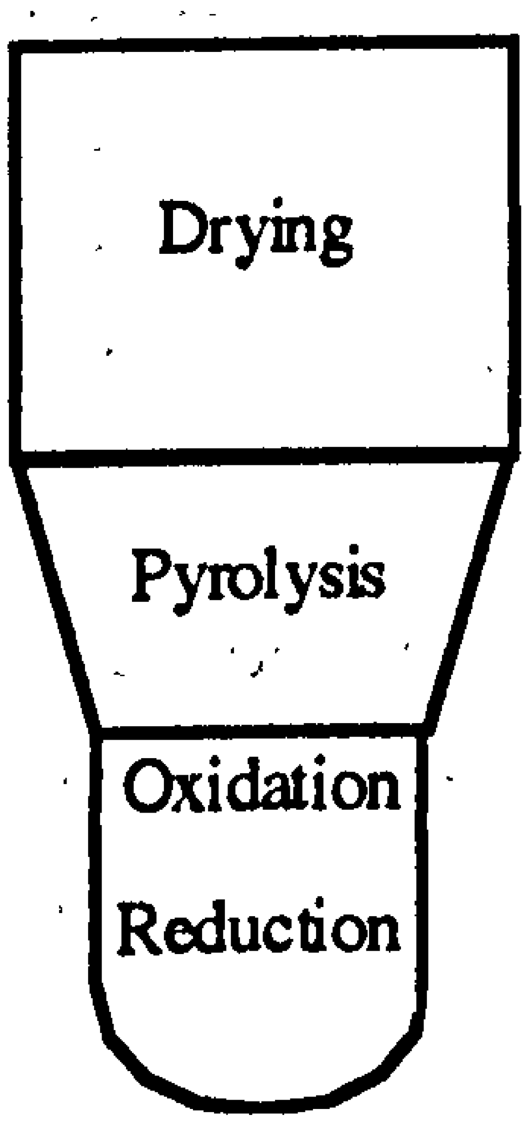

Figure 1
Stages of gasification

The downdraft gasification process can be split into four stages (Figure 1). Fuel enters at the top of the gasifier and progresses down through the drying, pyrolysis, oxidation and reduction zones. Each stage is dealt with in detail below.

DRYING

The heat from the oxidation zone is transmitted upwards, through the pyrolysis zone, to the chip at the top of the column. This causes the water in the wood to evaporate. It is important that the wood does not contain too much water or problems can occur. Evaporation of excessive water in the fuel will use too much heat; this can lead to ineffective drying or reduction in temperatures at lower stages. If the excess water is driven into steam, it can form a 'protective' jacket around the fuel reducing heat transfer (Williams, 1995). Both these effects will adversely effect the performance of the gasifier.

PYROLYSIS

The heat from the oxidation zone heats the fuel in the pyrolysis zone and in the absence of oxygen, it begins to degrade. When the temperature is between 150 °C and 500 °C the volatile constituents are driven off producing CO, CO_2, H_2, formic acid, acetic acid and complex hydrocarbons (ETSU, 1993). Since there is an absence of oxygen, the flammable components do not ignite until they reach the oxidation zone.

OXIDATION

This stage provides the heat that drives all the other reactions. Air is introduced through tuyeres and the fuel and gaseous products from the pyrolysis stage are partially combusted to produce charcoal and gaseous products. The temperature at this stage is important as most of the oils and tars produced in the pyrolysis stage must be removed from the gas before they enter the cooling system if costly cleaning is to be avoided. At temperatures of 1200 °C and above these oil and tar molecules combust to form CO_2 and H_2O or are thermally cracked into smaller hydrocarbon chains (ETSU, 1993). Keeping the oxidation zone uniformly above this temperature is vital if as much of the oils and tars as possible are to be treated (Kaupp and Goss, 1994; Garcia-Bacaicoa *et al.*, 1994).

REDUCTION

The fuel in the oxidation zone is only partially combusted. The resultant charcoal fuels the reactions in the reduction zone and produces the fuel gas. The heat from the oxidation zone reacts with the solids and gases to produce the fuel gases CO, H_2 and CH_4. The reactions are shown below (Kaupp and Goss, 1984).

$$C + O_2 = CO_2 \qquad dH = +394\ MJ.kg^{-1}.mole^{-1}$$
$$C + CO_2 = 2CO \qquad dH = -173\ MJ.kg^{-1}.mole^{-1}$$
$$C + H_2O = CO + H_2 \qquad dH = -131\ MJ.kg.^{-1}mole^{-1}$$
$$CO + H_2O = H_2 + CO_2 \qquad dH = +41\ MJ.kg.^{-1}mole^{-1}$$
$$C + 2H_2 = CH_4 \qquad dH = +75\ MJ.kg.^{-1}mole^{-1}$$

The gas produced at the end of this process contains CO, CO_2, H_2, H_2O, CH_4 and several other trace chemicals. In air fuelled gasification most of the gas is N_2.

MECHANICAL DESIGN OF DOWNDRAFT GASIFIERS

There are three areas where the design of a downdraft gasifier can significantly vary; the hopper design, hearth geometry and air inlet design.

HOPPER DESIGN

The chip is held in a hopper prior to combustion and it is in this zone that drying and pyrolysis take place. The design of this hopper is important if the fuel is to flow smoothly into the oxidation zone.

HEARTH GEOMETRY AND AIR INLET DESIGN

The geometry of the hearth, within which the oxidation zone lies, affects the whole process. The design must allow sufficient fuel to be burnt at a sufficient temperature to provide heat for the other processes. The heat production within the oxidation zone must also be as homogeneous as possible so the oils and tars from pyrolysis can either be burned or thermally cracked (Kaupp and Goss, 1984; Garcia-Bacaicoa, 1994).

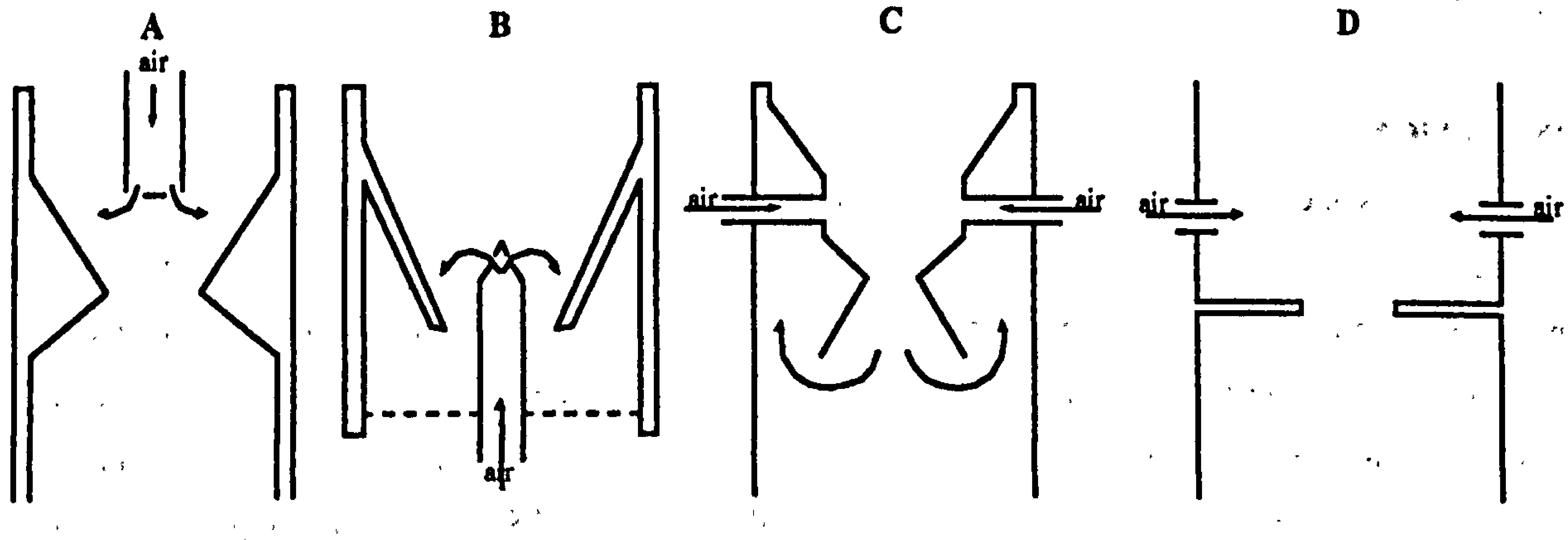

Figure 2. Hearth Geometry (Kaupp and Goss, 1984)

Variations in the geometry of the hearth and tuyeres fall into four main categories (Figure 2). Selection of a geometry depends upon the temperatures that are going to be reached, the materials available for manufacture, the size of the gasifier, the fuel and whether the air is blown into the system or drawn in. The simplest design is to use a choke plate at the bottom of a square profile hearth of circular cross section (Figure 2/D). Other designs (A, B and C) can have problems with high temperatures. If temperature cannot be kept low enough then there may be problems with the materials melting and welds failing (Dawson, 1998).

The limiting factor on size of unit is set by the ability to maintain a homogeneously hot hearth, i.e. air distribution. A large throat (larger gas production) has more problems than a small throat (lower gas production) since the even distribution of air across its diameter is more difficult. The throat size also affects the flow of fuel through the gasifier and its ability to avoid the fuel sticking together and blocking the flow ('bridging') (Williams, 1995).

CONCLUSION

A downdraft gasifier running an internal combustion CHP generator set could provide a good solution for the scenario envisaged in Chapter 1. This is backed up by other analyses (Bridgwater and Evans, 1993; Hislop, 1991). If properly designed, pollutants could be kept to a minimum.

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CHAPTER 3

EXPERIMENTAL SET-UP OF A 30-KWE DOWNDRAFT GASIFIER SYSTEM

INTRODUCTION

Experiments were necessary to evaluate the feasibility of a small-scale biomass-to-energy conversion machine. Experimental work was based on a 30-kWe experimental downdraft gasifier. The choice of a downdraft gasifier has been explained (Chapter 2). The gasifier system is based upon a 'stand-alone', wood block gasifier produced by Fluidyne Gasification Ltd (NZ) (Williams, 1993). The gasifier supplies an internal combustion generating system that generates electricity into the local grid. The aim of the experiments was to assess the feasibility of producing electricity for 70% of the year from Short Rotation Coppice (SRC) wood chip.

For the system to be feasible it would be necessary for the machine to run stably, without significant human intervention, for periods of at least a day. The machine was designed to run on wood block and ran reliably on this fuel. Experiments with wood block gave an idea of the characteristics of the machine when operating properly. After these experiments, trials were done with wood chip to judge the effectiveness of the machine with its new fuel and find the areas, if any, where modifications were necessary.

EXPERIMENTAL SYSTEM

DRYING

The wood chip in the experiments needed to be dried before it could be used. It was assumed, after advice (Williams, 1995), that 15% would be a suitable moisture content for the feed to the gasifier. Facilities exist at LARS to dry wood chip in covered drying bays. Using a fan, air is blown through a chamber containing a heat exchanger through which the engine cooling water is being pumped. The air is then blown through grills in the floor of the drying bays into a layer of approximately 1m deep wood chip. The air inlet to the heat exchanger is ducted so that the air going into the heat exchanger passes through the generator's radiator before entering the system. This increases the amount of heat removed from the generator's cooling system. It would be possible to use more of the heat from the generator with a more efficient heat exchanger.

CONVERSION

A diagram of the gasifier and its filtration chain is shown in Figure 1. Figure 2 is a photograph of the gasifier system based at LARS.

THE GASIFIER

GENERAL

The Pacific Class downdraft gasifier, used at LARS, unlike many downdraft gasifier systems is a 'drawn' system rather than a 'blown' system. Drawing air through the system using a start-up fan starts the gasifier. The gas is burned directly (flared), to check its quality and to give the gasification process time to establish itself. When enough gas of a reasonable quality is being produced the fan is stopped and the engine started with the gas remaining in the system. Once the engine has started the gasifier is dependent on the engine to provide the 'pull' to maintain the gasification process and the engine is dependent on the gasifier for fuel. As the system is not blown there is no facility to over-produce gas, burning the excess when necessary, to compensate for decreases in gas quality. If the quality of the gas deteriorates the gasifier must increase gas production sufficiently to ensure the electricity generator's stability is not jeopardised. The system is not duel fuelled so increasing diesel or natural gas consumption cannot smooth out variations in gas quality.

The gasifier was designed for use in the tropics, running on wood block, for areas where grid connection was unfeasible. The exact design of the machine is subject to commercial confidence, so detailed drawings of the interior are not available. There are several differences in the conditions for which the machine was designed and those where it is proposed to use it. In the tropics labour is at less of a premium than in Europe. In most cases the machine would only have been expected to run for short periods each day, e.g. providing lighting in the evenings or running a sawmill. As a result of these operating criteria the machine has virtually no automation and the amount of fuel and ash which can be stored in the machine will only provide a few hours continuous running. The machine was designed for remote generation where it was not possible to import power from the country's electricity grid. If the fuel quality lessens, so that the machine generates less, lights may dim or a saw may slow down, but it will not cause other problems. However if a generating machine is connected to a large stable electricity grid, as in the UK, if the generator falters the machine must disconnect itself from the grid or face catastrophic results (Cogen, 1995). Thus, the gas flow and quality must be stable.

After gasification the product is a wet, hot and dirty gas. This gas is not suitable for conversion into energy (Kaupp and Goss, 1984). The filtration of the gas to remove particles is necessary to maintain the serviceability of the generating machinery. Cooling is necessary to remove water and increase the stoichiometric efficiency of the combustion process within the generating machinery.

The gasifier is housed outdoors, underneath a cover for safety reasons. The gas is piped between the gasifier and the unit. The engine generator system is housed within the same glasshouse as the drying bays. The heat from the engine jacket and exhaust are removed and fed into the piping which in turn feeds into the drying unit.

REACTION AREAS

The gasifier is fed on a batch basis, the fuel load being held in a hopper above the oxidation and reduction zones. This hopper can carry enough fuel for the gasifier to function for approximately two hours depending on the type and quality of the fuel. Within the hopper, drying and pyrolysis take place.

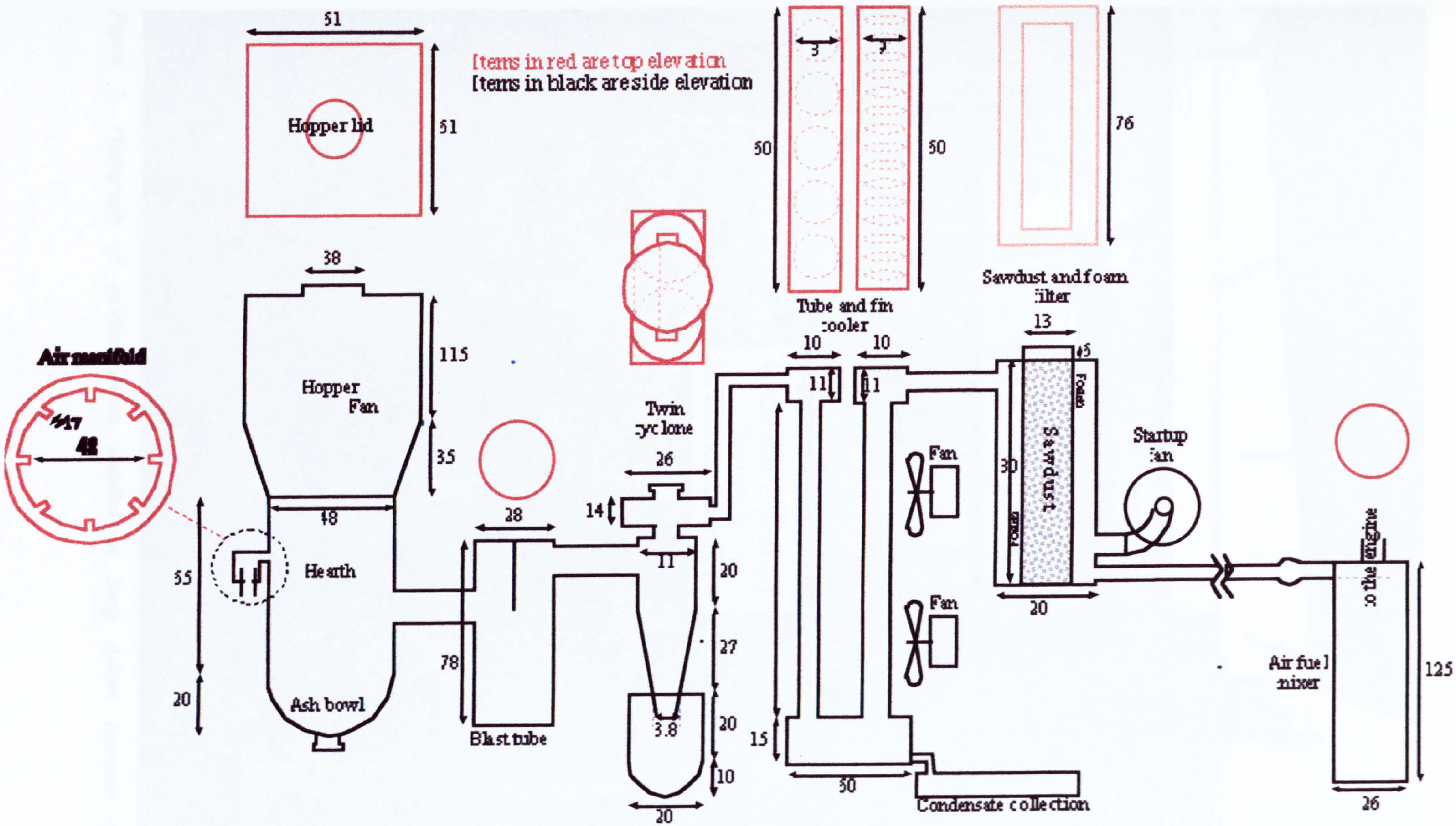

Figure 1. Diagram of gasifier and filtration chain

Figure 2. Photograph of gasifier system installed at Long Ashton Research Station.

The production of oils and tars from pyrolysis within the hopper can lead to problems. Oils and tars have a tendency to stick the fuel together and the smaller the size of the fuel particles, the greater this problem will be. The gasifier was supplied with an agitating system to relieve the problem. This agitation system was designed for use with wood block that has a particle size much larger than the proposed fuel, wood chip.

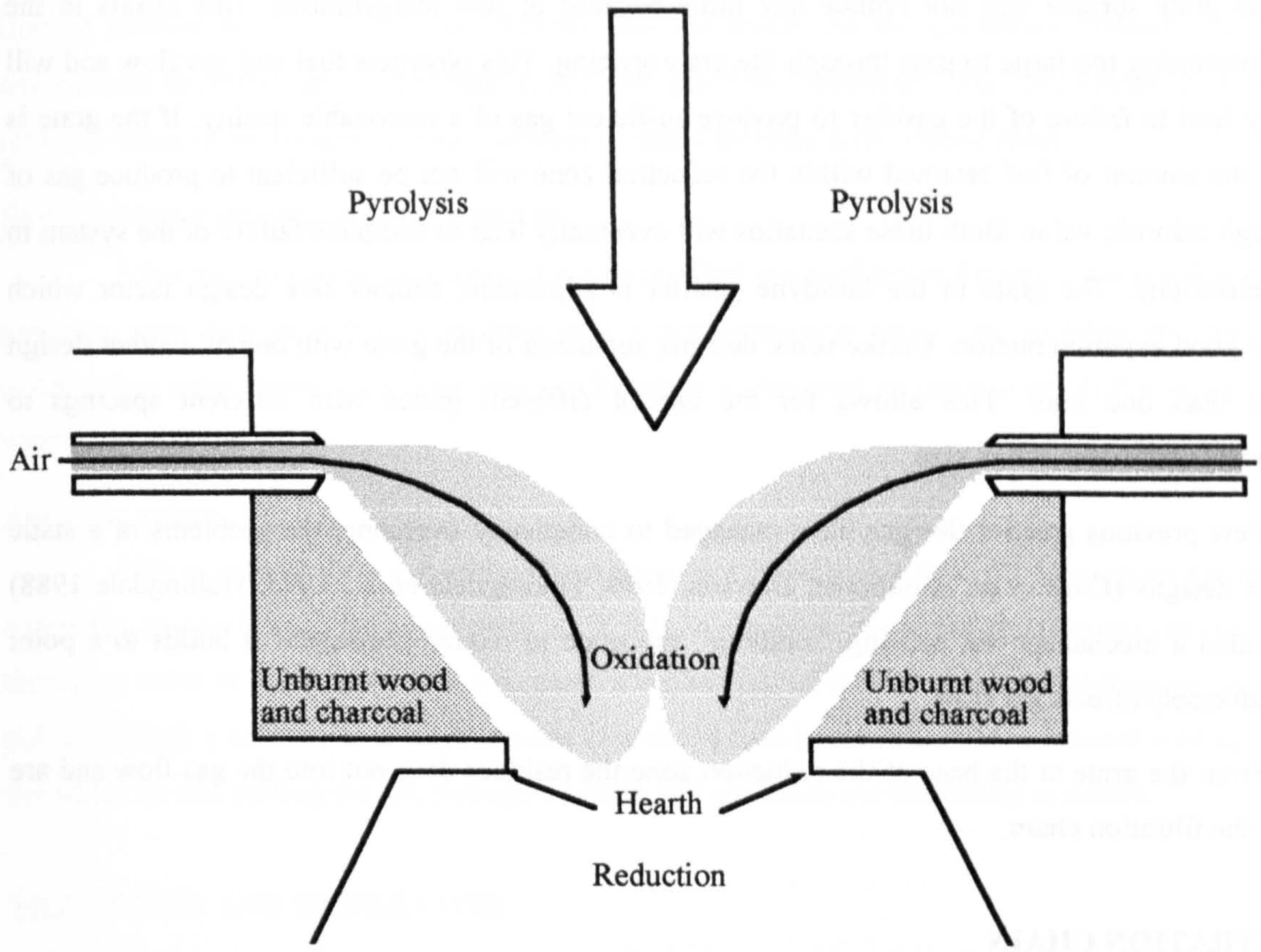

Figure 3. Schematic of hearth area showing tuyeres, throat and air flow.

The flow of the fuel throughout the reaction stages is due to gravity. From the hopper the fuel falls through a constriction into the oxidation 'hearth'. The presence of this constriction can add further to the fuel flow problems mentioned above. A schematic of the oxidation zone is shown in Figure 3.

The right-angled profile of the hearth offers some protection against the high temperatures achieved during combustion. The fuel naturally follows a diagonal path from the constriction at the base of the hopper to the throat. It is in this area that the combustion and therefore high temperatures occur (≅1600 °C). Surrounding this area, unburnt chip and charcoal provide good thermal insulation. The design also incorporates tuyeres which stand proud of the combustion zone walls thus distancing the burning material from the walls. The design of the hearth is such that the area at the throat is small enough to allow access for air across its diameter. This alleviates cold spots but is also large enough to allow sufficient fuel flow.

The throat geometry is critical to the performance of any gasifier (Kaupp and Goss, 1984; Garcia–Bacaicoa, 1994). The diameter and height of the throat in the Fluidyne gasifier can be modified by inserting rings into the throat. This allows a degree of experimental flexibility rarely found in downdraft gasifiers.

The most important stage of gasification is the reduction; the stage at which the fuel gas is produced. The reduction area expands downwards from the throat to a constant diameter. At the base there is grate or 'spillage plate' which, by means of its position and gap size, regulates the fuel flow and retains the charcoal for long enough to produce a gas of useful composition. If the grate is too low the temperature at the grate face will also be too low and 'frozen reduction' occurs. This happens when the fuel at the grate surface will not reduce any more because of low temperatures. This results in the particles remaining too large to pass through the grate spacing. This obstructs fuel and gas flow and will eventually lead to failure of the gasifier to produce sufficient gas of a reasonable quality. If the grate is too high, the amount of fuel retained within the reduction zone will not be sufficient to produce gas of high enough calorific value. Both these scenarios will eventually lead to complete failure of the system to produce electricity. The grate in the Fluidyne gasifier is adjustable, another rare design factor which allows for good experimentation. Unlike some designs, replacing of the grate with one of another design takes less than one hour. This allows for the use of different grates with different spacings to accommodate variations in fuel size.

Few previous gasifier designs have managed to completely overcome the problems of a static grid. Most designs (Chee *et al.*, Unknown; Dawson, 1998; Hollingdale *et al.*, 1995; Hollingdale 1988) have included a mechanism for moving, 'riddling', the grate to reduce pressure if it builds to a point where it adversely affects gas flow.

From the grate at the base of the reduction zone the residues drop out into the gas flow and are filtered in the filtration chain.

THE FILTRATION CHAIN

The filtration chain is divided into the following components; Ash Bowl, Blast Tube, Twin Cyclone, Tube and Fin Cooler, Sawdust/Polymer Foam Safety Filter and Air Fuel Mixer.

ASH BOWL

After the gas and the entrained impurities pass through the grate at the base of the reduction zone they enter the ash bowl Figure 1. Here the effective diameter through which the flow must pass increases substantially and it must also turn a corner. These two factors combine to slow the gas flow. As the gas slows so does its ability to retain particles. Consequently the ash bowl collects the larger particles of debris contained within the gas flow.

BLAST TUBE

The blast tube uses the same principle as the ash bowl. The gas enters through a pipe and is forced around a corner into a larger diameter tube. Thus the heavier particles left within the flow are removed. These removed particles collect in the bottom of the blast tube. The blast tube is also within a casing along with the cyclones and the cooler. This casing has a constant stream of ambient air blown over it, so there is a cooling effect.

TWIN CYCLONES

At this stage the larger particles have been removed from the flow and what remains is dust-like particles of varying sizes. These must be removed using a more efficient method than that used in the blast tube and ash bowl. The gas passes into one of two cyclones designed to centrifugally remove the particles from the flow. The removed 'dust' is collected in a sealed box at the base of the cyclones. Again there is a cooling effect.

TUBE AND FIN COOLER

The gas enters a cooler directly after leaving the cyclones. The fans that are used to force the flow of ambient air through the case directly abut the cooler. As the gas passes through this cooler its temperature decreases and water held within the gas flow condenses. This condensation process also removes some of the remaining solid particles as water droplets form around them.

SAWDUST/POLYMER FOAM SAFETY FILTER

After the gas leaves the coolers it enters the final stage of direct filtration, the sawdust filter. The gas must pass through a fine mesh foam into a box containing rough, dry sawdust and then through another fine mesh foam. This final stage of filtration is designed to remove any left-over particles and water from the gas.

AIR FUEL MIXER

This is not strictly a part of the filtration system but acts as a final filtration stage. Before the gas enters the engine it must be mixed with air if it is to combust. Ambient air is drawn into the gas flow through a valve in the ducting. The two gases must be well mixed for efficient combustion, so the gas is pulled through a nozzle into a large circular chamber where it vortexes. The combined cooling effects of the added air and pulling the gas through a nozzle will condense out remaining moisture.

THE ENGINE AND GENERATOR

The engine and generator set is a standard system produced by Countryman Ltd. It comprises is a 6 cylinder, 7.8 litre, engine fitted with a gas carburettor, spark ignition and a generation system. The unit was designed to work at 70 kWe on natural gas but has been adjusted to run at a maximum of 30 kWe on the lower calorific value producer gas. The system is automated with a Heinzman controlled carburettor. The engine runs at approximately 2000 rpm.

EXPERIMENTAL PROGRAMME

In September 1993, before the author's involvement in the work, the system was installed and run for several short trials on wood chip. These proved to be problematic and the system was left idle until February, 1994. In February 1994 trials with wood block were proposed to gain some knowledge of the machine's operation using its preferred fuel, and to ensure that the system was installed correctly. These trials ended when the engine failed as a direct cause of abortive attempts to run on wood chip the previous September.

WOOD BLOCK

Table 1. Variables measured during monitoring of gasifier.

Variable to be measured	Placement of measurement
Pressure of gas inside gasifier's filtration chain	Blast-tube, Sawdust filter
Temperature of gas inside gasifier's filtration chain	Blast tube
Demand for gas by engine	Engine gas inlet
Electricity being generated	Generator

After the repairs on the engine several trials were done using wood block as the fuel. Measurements, Table 1, were taken at this stage so that the data could be used as a reference to judge the performance of the machine on wood chip. Information on the pressures and temperatures obtained within the system were recorded along with information on the filtration chain output.

WOOD CHIP

Wood chip was available from a number of different harvesting machines and from a number of different crops of varying age and size. The majority of this was dried within the drying bays at LARS. After the wood block trials a modified grate was added for use with wood chip. The experiments with the machine using wood chip as a fuel had three aims.

1. **Determining efficiency and stability.** To determine the efficiency and stability of the gasification process when using wood chip several runs were completed. During these runs the pressure and temperature at the blast tube, the pressure at the filter, the kWh generated and the fuel used were measured. From this information, an idea of the stability of the gasification could be gathered and a value for specific fuel consumption of fuel used could be calculated.

2. **Investigate efficiency and output of filtration.** Measuring the outputs from the individual filtration components for a number of experiments would allow an investigation into how factors like moisture content of fuel, ambient temperature etc. related to the amount of waste.

3. **Investigation of feasibility and modifications.** Many runs were undertaken, and the stability and practicality of different aspects studied. Using this observational data, modifications to the mechanics of the system could be carried out to try to increase the efficiency and feasibility of the system.

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CHAPTER 4

RESULTS OF EXPERIMENTAL WORK ON 30-KWE GASIFIER

WOOD BLOCK TRIALS

The wood block fuel (average size 447mm, 170mm, 149mm) was used in four runs for which the pressures and temperatures were recorded. The pressure and temperature measurements taken at the blast tube are representative of the pressures and temperatures in the reaction chamber. The pressures within the reaction chamber will be related to the obstructions caused to the flow by the reactions. A constant pressure would imply that the reactions were at a stable state. Similarly, a constant temperature would imply that some stability had been reached with the chemical reactions. It is accepted that equilibrium will not be reached in such a reactor (if it is possible at all). An ideal situation would not be one of perfect equilibrium but one where the variations in temperature and pressure were minimised. Figures 1 and 2 show the changes in temperature and pressure at the blast tube over a given period.

Figure 1 shows the changes in temperature against time at the blast tube. For the four runs examined here, it is possible to fit an exponential curve. An exponential curve was chosen as it best represents the probable processes taking place as the chemical processes stabilise and the temperature in the gasifier system stabilise. These curves show that the temperature at the blast tube, and therefore in the reaction chamber, are stabilising. The temperature at this stage varies from run to run, this could be due to a number of reasons. Variations in the fuel, ambient temperature, initial status of oxidation zone could affect the temperature measured at the blast tube. However, it is possible to draw the conclusion that a stable temperature of approximately 350 °C is being reached.

Figure 2 shows the changes in pressure measured at the blast tube against time. It is much harder to draw any conclusions from these readings. Although in the longest run (20/04/94) the pressure appears to be stabilising towards the end, there is no statistical evidence to prove this and the other runs do not aid this conclusion. The wild variations in pressure are, it is suggested, due to obstructions to the fuel flow in the reduction area/grate and holes forming in the oxidation zone due to 'bridging'. These results are discussed in a later section.

WOOD CHIP

The purpose of the wood chip trials was:

1. To determine whether the gasification process could be made stable and efficient.

2. To investigate the efficiency and output of the filtration chain.

3. To modify the machine so that it worked efficiently and to investigate the feasibility of modifying the machine to run the way envisaged in the scenario described in Section 1.

The wood chip used varied in size, willow variety, age and condition. The variations in type were not considerable and every attempt was made to ensure consistency. To give an idea of the chips used an analysis of a representative sample is included below.

CHIP SIZES FROM BUCKFAST-LEIGH HARVESTING TRIALS BY THE FORESTRY COMMISSION

A sample was taken from the top of the heap of wood that had been taken from the Claas harvester trials at Buckfast-Leigh. The sample had been suitably mixed. Total sample size was 324g. Sizes referred to are the length of the maximum axis.

Table 1. Size distribution within a representative chip sample.

Size (mm)	% mass
0-20	14
20-30	36
30-40	33
40-50	6
50 +	9
Bark	2

The chips had a moisture content of 51.4 % when harvested and had been oven dried before the measurements below were done, giving a moisture content of approximately zero.

DETERMINING THE STABILITY OF GASIFICATION OF WOOD CHIP

As with wood block, the pressures and temperatures at the blast tube can be related to the stability of the processes within the gasifier. Using information from seven runs for which comprehensive pressure and temperature data were recorded, similar investigations can be carried out. Figures 3 and 4 show the progress of temperature and pressure at the blast tube over time respectively.

Figure 3 shows the changes in temperature at the blast tube against time. Similar to the results from the wood block trials, those from separate runs can have exponential curves fitted to them. They also show the same trend to stabilise after a given time. However, compared to wood block, the temperature at which they stabilise is significantly higher; being approximately 400 °C for chip compared to 350 °C for block. With wood chip the time it takes to reach this equilibrium varies considerably between approximately 1000 seconds and 5000 seconds. However, the average of approximately 2000 seconds is similar to the wood block trials. The increase in temperature is probably due to the higher temperatures that can be achieved with a fuel of smaller particle size, and therefore greater surface area per weight which wood chip has compared with wood block.

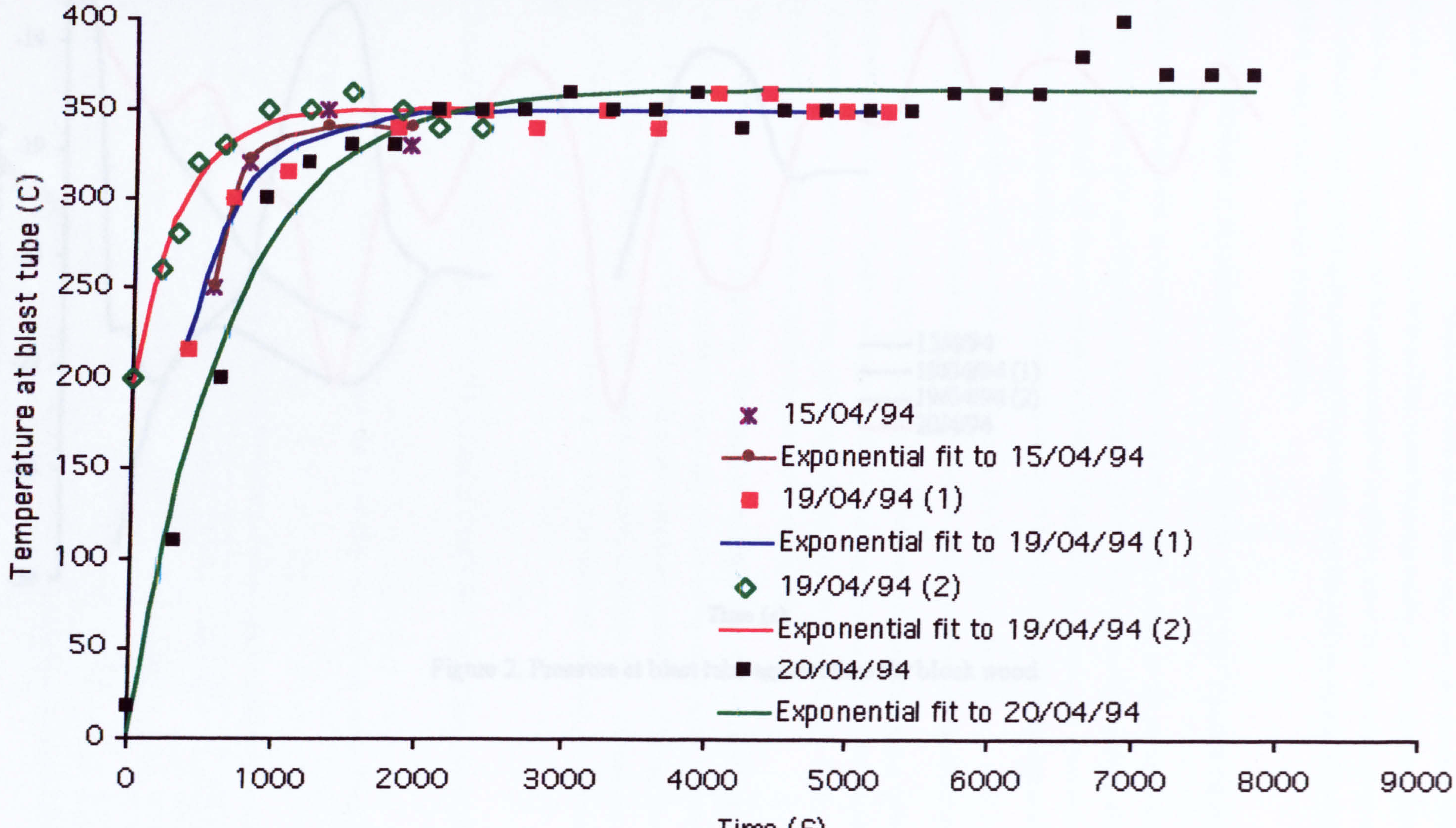


Figure 1. Temperature against time for block wood trials

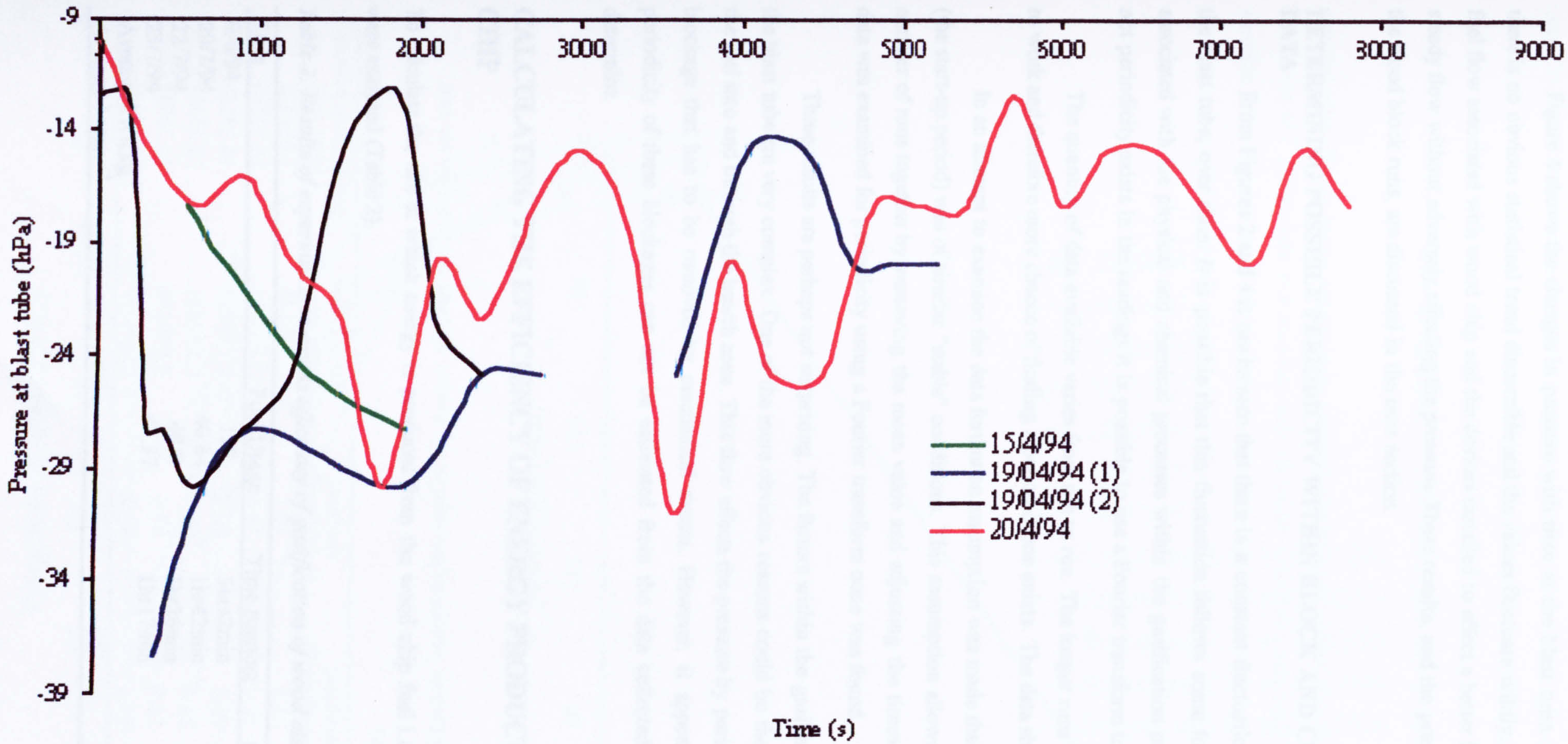


Figure 2. Pressure at blast tube against time for block wood

Figure 4 shows the changes in pressure with time at the blast tube. As with the wood block trials there is no obvious statistical trend discernible and the values fluctuate wildly. This is due to problems with fuel flow associated with wood chip and the devices installed to effect a better flow did not manage to achieve steady flow without adversely affecting the pressure. These results, and the pressure against time results from the wood block runs, are discussed in the next section.

DETERMINING POSSIBLE PERIODICITY WITHIN BLOCK AND CHIP TRIALS PRESSURE DATA

From Figures 2 and 4 it can be seen that there is a constant fluctuation in the pressure, measured at the blast tube, over time. It is possible that this fluctuation follows some form of periodicity that can be associated with the physical and chemical processes within the gasification process. To examine whether or not periodicity exists in the readings it is possible to use a Fourier transform to analyse the data produced.

The quantity of data available varies from run to run. The longer runs provide more data with which to work and therefore more chance of finding a period if one exists. The data showed no significant period.

In an attempt to examine the data further an assumption was made that the data after a certain period (the start-up period) was of similar "stable" conditions. This assumption allows one to 'stitch' the data from a number of runs together by removing the mean value and adjusting the times accordingly. Again when this data was examined for periodicity using a Fourier transform none was found.

These results are perhaps not surprising. The factors within the gasifier that influence the pressure at the blast tube are very complex. One of the more obvious reasons could be the effect of the physical flow of the fuel into and through the hearth zone. This flow affects the pressure by periodically blocking the hearth, a blockage that has to be removed by mechanical means. However, it appears from the analysis that the periodicity of these blockages can not be estimated from the data collected and may be too complex to determine.

CALCULATING THE EFFICIENCY OF ENERGY PRODUCTION FROM WOOD CHIP

To calculate the rate at which energy is produced from the wood chip fuel i.e. J/sec results from three runs were analysed (Table 2).

Table 2. Results of experiments to assess efficiency of gasification of wood chip for electricity production.

Date	Fuel Usage	Time running	total kWh	$KWh.kg^{-1}$
9/6/94	120	5hrs2min	111.9	0.9325
20/7/94	40.84	1hr42min	36.3	0.8888
22/7/94	48.9	1hr26min	38.9	0.7955
25/7/94	47.37	1hr17min	32.7	0.6903
Average $kWh.kg^{-1}$				0.8268
Average $J.tonne^{-1}$				2.976×10^9

If the process of generating 1 kWh of electricity produces 2 kWh of heat as usable waste (Cogen, 1995) then 1 tonne of wood chip produces 5.953×10^9 j of heat.

EFFICIENCY AND OUTPUT OF FILTRATION COMPONENTS

The quantity of material collected by each of the filtration components varied significantly between runs. An investigation to see if there was a definable reason for this variation was undertaken. The content of each of the filtration chain's components was measured after each of six runs. Each run was of a different duration. To compare the results (Table 3) the weights and volumes have been converted to figures per minute of operation.

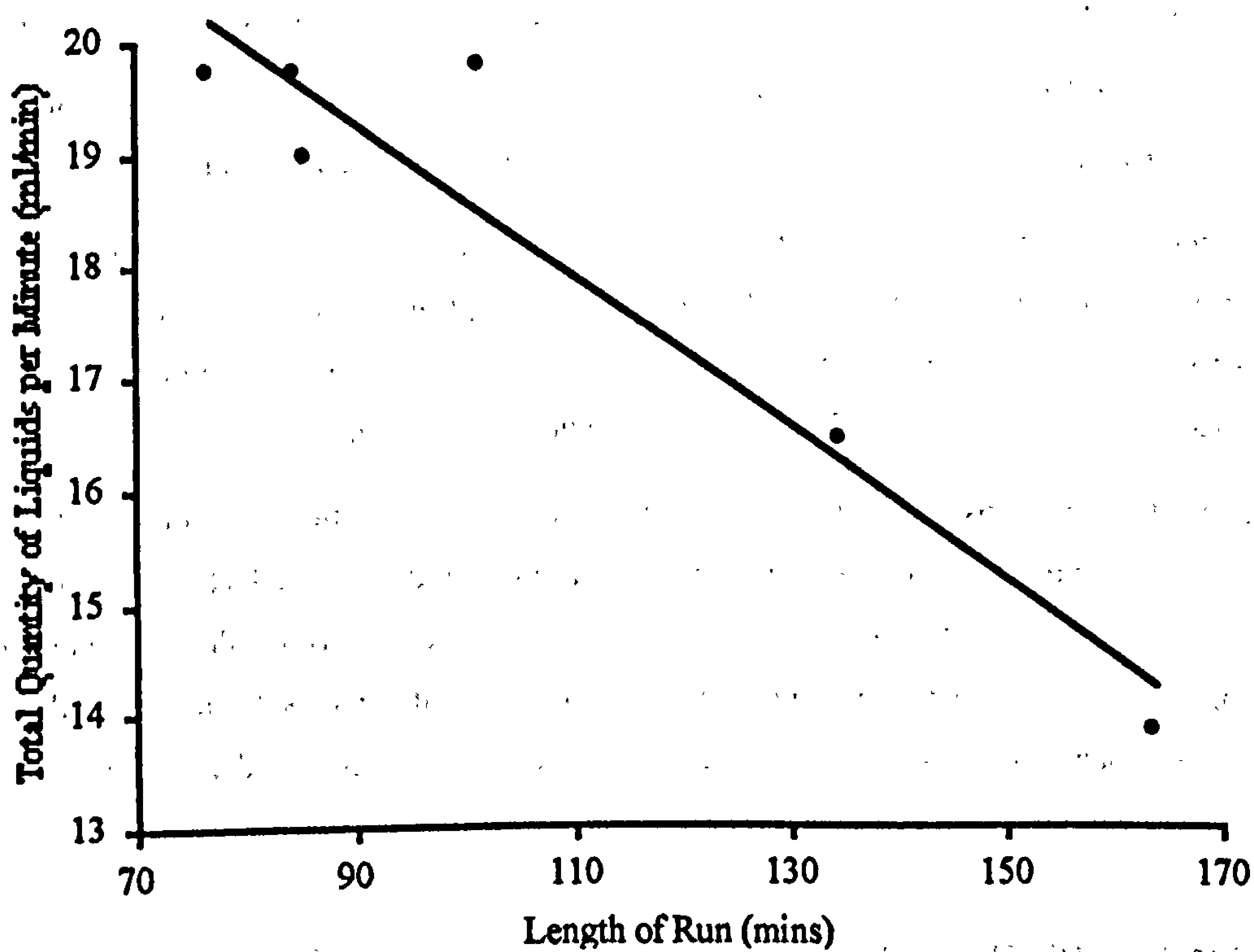
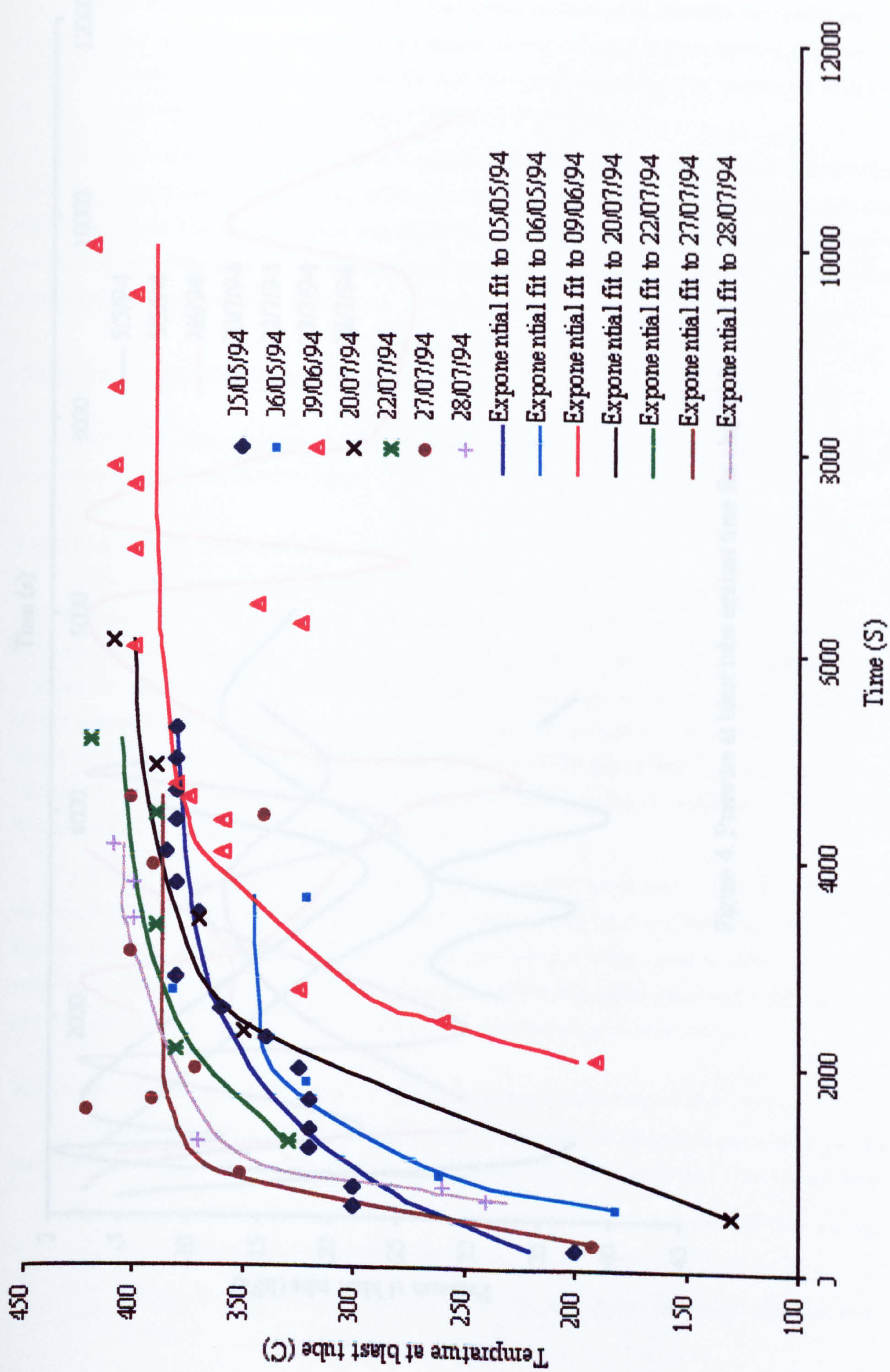


Figure 5. Total quantity of fluid waste produced per minute of runtime against the length of the run.

Table 3. Filtration chain output.

Date	Length of Run (min)	Ambient Temperature °C	Ambient Humidity (%)	Total Solids. Minute^{-1} (kg.m^{-1})	Total Liquids.Minute^{-1} (ml.m^{-1})
19/4/94	135	12.5	70.1	0.118148	7.631926
2/6/94	85	18.1	74.8	0.224471	14.47565
7/6/94	164	16.5	90.4	0.114756	10.37268
20/7/94	102	23.3	69.7	0.237451	12.55167
22/7/94	86	23.9	57.4	0.293256	12.33035
27/7/94	77	19.4	89.8	0.264545	15.97792


Temprature at blast tube (C)
Time (S)
450
400
350
300
250
200
150
100
0
2000
4000
6000
8000
10000
12000
05/05/94
06/05/94
09/06/94
20/07/94
22/07/94
27/07/94
28/07/94
Exponential fit to 05/05/94
Exponential fit to 06/05/94
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Exponential fit to 28/07/94

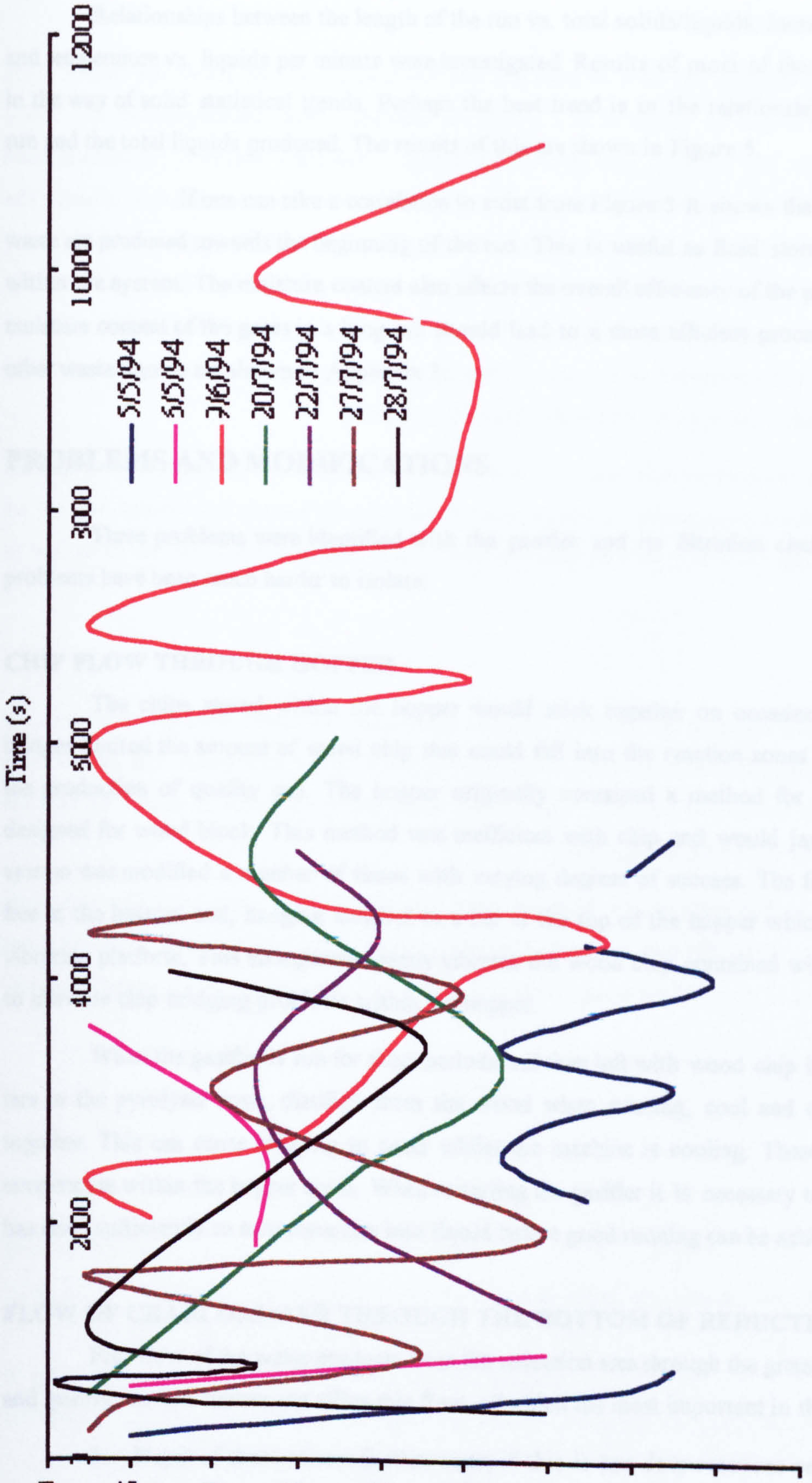

Figure 4. Pressure at blast tube against time for chip trials

Relationships between the length of the run vs. total solids/liquids, humidity vs. liquids per minute and temperature vs. liquids per minute were investigated. Results of most of these investigations show little in the way of solid statistical trends. Perhaps the best trend is in the relationship between the length of the run and the total liquids produced. The results of this are shown in Figure 5.

If one can take a correlation to exist from Figure 5 it shows that the fluids produced in the waste are produced towards the beginning of the run. This is useful as fluid storage and disposal is an issue within the system. The moisture content also affects the overall efficiency of the process and reductions in the moisture content of the gases in a long run should lead to a more efficient process. Graphs derived from the other waste figures are shown in Appendix 3.

PROBLEMS AND MODIFICATIONS

Three problems were identified with the gasifier and its filtration chain. The exact causes of the problems have been much harder to isolate.

CHIP FLOW THROUGH HOPPER

The chips stored within the hopper would stick together on occasion, forming 'bridges'. These bridges limited the amount of wood chip that could fall into the reaction zones. This was not conducive to the production of quality gas. The hopper originally contained a method for freeing bridges, which was designed for wood block. This method was inefficient with chip and would jam and cease to work. This system was modified a number of times with varying degrees of success. The final solution uses two bars, free at the bottom end, hanging attached to a bar at the top of the hopper which, in turn, is attached to a vibrating platform. This arrangement gently vibrates the wood chip contained within the hopper and appears to alleviate chip bridging problems within the hopper.

When the gasifier is run for short periods and then left with wood chip in the hopper it appears that tars in the pyrolysis zone, distilled from the wood when running, cool and condense bonding the chips together. This can cause bridging to occur whilst the machine is cooling. These bridges consolidate as the temperature within the hopper cools. When restarting the gasifier it is necessary to wait until the temperature has risen sufficiently to turn these tars into liquid before good running can be achieved.

FLOW OF CHARCOAL/ASH THROUGH THE BOTTOM OF REDUCTION ZONE

Free flow of the waste products from the reduction area through the grate is essential to gas quantity and quality. Several factors can affect this flow, of which the most important in the LARS system were:

1. Depth of char in the reduction zone; if this is too deep reactions cease, fuel does not reduce in size and, thus, cannot fall through the grate (frozen reduction).

2. Impurities, either occurring naturally within or adhering to the wood chip can cause slag formation.

3. Oversized fuel particles.

All of these factors can obstruct the flow of both gas and fuel/waste particles above the hearth. This problem is not unique to this gasifier (Chee *et al.*, Unknown; Dawson, 1998; Hollingdale *et al.*, 1985; Hollingdale, 1988). Initially, the problem was approached using a vibrating platform; vibrations were transmitted through a metal bar to the reduction area casing. This did not have any noticeable effects. The design of the grate is such that its height can be adjusted using a spring-loaded adjuster bolt. A small modification allowed this system to be motorised causing the grate to rise and fall by 10 mm (Chapter 3). This solution is similar to that used by other designers (Dawson, 1998; Hollingdale, 1988). Other solutions have usually involved a circular movement of the grate (Chee *et al.*, Unknown), however the design of the grate in the gasifier under study here does not allow this form of movement.

Intermittent use of this arrangement alleviated the problem. The development of some type of rule for the timing and length of cycles is problematic. It was possible to control with human intervention but no set routine seems to work. Linking the timing to the pressure sensors and a control system may be an option in the future.

FILTRATION

The gas-cleaning chain operated inefficiently. Particles that should have been removed early on in the filtration chain were being carried further down the system. This problem had a dual cause. The gas-cleaning chain is of inadequate size for the rate of gas flow. This caused some fine particles to be carried beyond the cyclone, which is too small to cope with the gas flow.

The other problem is that each of the filtration steps has a collection zone, in which the waste material is kept. Once this has filled, the material being filtered out stops being removed and is carried down the system. Increasing the size of some of the components and of the collection zones or automated removal, should be a priority.

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CHAPTER 5

THEORETICAL BACKGROUND TO ENERGY ANALYSIS OF INDUSTRIAL AND AGRICULTURAL SYSTEMS

INTRODUCTION

Energy Analysis (EA) is a tool that has many uses. A mechanical, biological, chemical, or any other form of system or process uses energy in its operation. All these systems or procedures could be made more efficient if the quantity of energy that they use, per unit of output, were to be minimised. A wish to understand simple machines and processes started the trend towards EA and from there EA expanded to cover entire systems with all their ancillary machines and processes. To begin to minimise the energy usage of a system one must know what all the processes are and how they affect the overall energy usage. This understanding of the energy use of systems is the foundation of modern energy analysis. Once this understanding has been achieved, the knowledge can be used to attempt to optimise the systems.

The simplest form of EA looks at a single machine or chemical process. As methods of EA have progressed, however, EA is being used more and more to look at whole systems. A whole system might be an entire chemical refining plant rather than just one of the processes, or an entire coal to electricity cycle rather than just the boiler/steam-turbine process. On an even greater scale EA can be used to look at systems on a national or international scale such as the UK steel industry or world wheat. This increased scope gives a greater ability to optimise systems but involves additional complications. The definition of the system and decisions as to what to account for add complications that will be discussed later.

Energy Analysis has existed in some form since the 1920s (Mortimer, 1991), but has only been in wide use since the 1960s (Jones, 1989). The oil crisis of 1973-74 caused a surge of interest in the minimisation of energy use. EA started to be widely used in the 1960s and 1970s. Many different groups were using many different techniques. In 1974 a workshop organised by the International Federation of Institutes of Advanced Study (IFIAS) recommended a common set of 'rules' for future energy analysis (IFIAS, 1974). These rules are still in use today, but a better understanding of systems and work on the theory of EA have led to a debate about the techniques and methods. As a result, ideas are beginning to fragment, once again leading to the use of varying methods of analysis. This variation can lead to some confusion regarding the methods used in an Energy Analysis and it is the purpose of this chapter to explain the choice of method undertaken by the author.

ENERGY ANALYSIS OF ENERGY PRODUCING SYSTEMS

Energy Analysis is most often used in industrial situations where the production of material goods or the provision of a service is the primary task. Here EA is used to minimise the energy required to produce a unit of production or a unit of service. The analysis of energy production systems using EA follows a similar programme. EA is a tool that can be used in conjunction with economic analysis and environmental studies to determine the feasibility of a system. An energy production system produces energy in units of joules, kWhrs, therms or BTUs, all units of energy that have associated energy costs in their production. There is however a difference between production of energy and goods or services. The production of energy becomes unfeasible when it takes more energy to produce than it contains itself per unit of output. It will become questionable before this ratio is reached. In a goods or services situation there is no physical product that can be measured against the energy usage to determine its feasibility.

This work is interested in the EA of biomass-to-energy systems and therefore the following description of EA has been written as an introduction to the theory of Energy Analysis for that scenario.

Conventional analysis of biomass-to-energy systems has been done, and is still done, using economic methods. Using only this form of analysis to judge the feasibility of a system has its drawbacks, as will be discussed in the next section; EA is seen as a complementary method.

ENERGY ANALYSIS AND ECONOMIC ANALYSIS

EA can be used to look at the feasibility of a system as can economic analysis and they should be considered as complementary. It is however worth noting the differences between the two. In an economic analysis, the monetary inputs to a system are accounted for and the monetary outputs are measured. Using these two sets of figures a number of results can be produced e.g. profit, return on investment, payback period. An Energy Analysis is similar, the energy inputs and outputs are accounted for and using this information a number of results can show the 'energy profitability' etc.

In economic analysis the unit is monetary (e.g. $ or £) whereas in Energy Analysis the unit is the Joule (J). This 'absolute' measure has its advantages. Monetary units can fluctuate daily. However in Energy Analysis the energy values attributed to machinery, materials and fuel consumption change much more slowly as technology develops to minimise the inputs. As a result an Energy Analysis is likely to date much more slowly than an economic analysis.

The price of the product (in the following analysis it is energy) will also fluctuate within the economic market place. As Goldthorp (1996) points out 'when imperfect types of competition prevail, the demand and supply curves are distorted' and 'under these circumstances, the price fixed will not be economically efficient'. This distortion can lead to the misevaluation of some energetically and socially beneficial solutions.

Another reason that Energy Analysis is a useful measure of the feasibility of a system is in the comparison of energy production methods. A new energy production method will require expenditure on development, research, acquiring land and machinery. Some of the older developed energy sources in the UK inherited much of this infrastructure from the old nationalised industries. This makes a direct comparison of the economic benefits difficult. An Energy Analysis of the present technologies removes many discrepancies and allows a more accurate analysis.

Another difference between energy and economic analysis is that all forms of energy use some type of energy in their creation. This energy must be accounted for in conjunction with the calorific value of the fuel used to run a machine.

In recent years economic analysis has developed in an attempt to address the above problems. The inclusion of factors for pollution and the use of fossil fuel resources in an effort to internalise some of these external costs (Goldthorp, 1996) has accounted for some of the inaccuracy of previous economic methods of evaluating systems.

The most well known of these factors is the 'Carbon Tax'. This prospective tax on the use of fossil fuels is based upon both direct and indirect energy usage deriving from fossil fuels. It can be argued that this taxation if applied (either in reality or theoretically) will make economic comparisons of fossil based energy production systems and renewable energy systems more accurate.

ENERGY INPUTS

It is possible to relate all forms of energy to one unit of measurement. In 1974 the IFIAS workshop recommended that all energy requirements and outputs should be measured using the *Système Internationale* unit for energy, the Joule (J). This convention has been adhered to in all the following work. However in the analysis that follows energy usage is at a level where for the sake of clarity the unit Mega Joule (MJ) or $J \times 10^6$ is often used.

All the inputs to a system which aid the production of a product will consume energy, but all this energy is not necessarily used directly. A good example is the addition of fertiliser to a crop. This process involves the use of energy, but the energy is not absorbed by the crop to increase its mass or energy value directly. Inputs of energy in this situation increase the ability of the crop to utilise an existing flow of energy i.e. the sun.

The definition of direct and indirect energy is important to an understanding of the energy analysis undertaken in this research. The definition that follows is the definition used throughout. The inclusion of indirect energy in conjunction with direct energy is important if a good representation of a system is to be achieved. This section also includes an explanation of the direct and indirect components in fuels. This is especially important in systems where the primary product is energy (fuel of some description).

DIRECT ENERGY INPUTS

In every production system direct energy inputs come from fuels or other energy sources which are used to perform functions within the system. Examples of direct inputs are fuel used in transportation, electricity used for lighting, gas used for heating, etc. These inputs can be easily accounted for if the facilities to measure their usage are available. Knowing the fuel consumption of a bulk carrier such as a truck would give a value for the quantity of the fuel that was used. The calorific value of this fuel is the direct input into the procedure of transportation. If the analysis were done in more detail then the lubricating oil usage during the journey would also be measured. All inputs of this type would be summed to give a value for the direct energy input.

INDIRECT ENERGY INPUTS

Indirect energy usage is often referred to as 'embodied energy usage'. Energy expended in producing any goods or services is passed on to the use of those goods or services. For example, a tractor 'contains' energy from the production of its chassis, panels etc. The steel used in these parts contains energy from the process used to produce it from iron ore. The iron ore contains energy from mining. In turn each of the machines and processes associated with each of these steps contains energy from all its previous stages. When the product or service is said to 'contain' energy from that process it does not mean that the goods or service has energy stored within its structure but rather that it has that quantity of energy attributable to it.

If all the energies associated with a particular product or service are summed up, this gives a value for the indirect energy of that item. To return to the example of the tractor once all the materials in its construction and the energy of its construction are accounted for, that tractor has an 'embodied energy' value. If the lifespan of the tractor can be determined, a value for the use of that tractor per hectare or per hour can be attributed to the use of that tractor; this is the indirect energy usage.

It is possible to continue to account for the energy of a product or service until one arrives at a level that is considered 'free'. This level would in almost all circumstances be the earth or solar level. However, to do this would be time-consuming in the extreme for anything other than the simplest product. At some point this process must be simplified by deciding on a level beyond which inputs are considered to be insignificant. The consensus is that the line is drawn after the manufacture of the product or service that is being used (Foster, 1993). For instance, considering the example of the tractor again, the energy cost of producing the tractor and the materials is considered, but the energy cost of producing the machinery that produced the tractor is not.

Any materials, which are consumed within a process, contribute to the indirect energy cost of the system. Each individual material would have had energy expended on it in obtaining the raw materials, manufacturing, transporting, packaging etc. In practice the determination of indirect energy usage by calculating the embodied quantity of a product or service would be too time consuming if it were done specifically for every machine. Figures are available for the embodied energy content of different types of machine by mass, horse power etc. Using these values an estimate of reasonable accuracy for the indirect energy content can be found.

Before discussing methods of Energy Analysis, the following section will deal in more detail with the energy associated with fuel usage.

FUEL INPUTS

Fuels are a direct energy usage by a system, but fuels also have an indirect component. Fuels are produced using industrial methods and transported to their end use point using some mechanical or electrical method. These processes consume energy and consequently the energy, which a system uses in consuming fuel, is made up from the calorific value of the fuel, plus a contribution from the production and transport. Boustead and Hancock (1979) showed that 8.47 $MJ.kg^{-1}$ is used in the production and transport of oil-based fuels. This compares with the calorific energy content of oil-based fuels of between 42.60 $MJ.kg^{-1}$ and 46.53 $MJ.kg^{-1}$. Although these quantities are small when considered in terms of 1 kg or 1 kWh they become significant when considered in the large quantities that some systems use.

ENERGY REQUIREMENTS

The total amount of energy necessary for one unit of input or output is called the energy requirement. There are two forms of energy requirement, gross and net. The gross energy requirement is the summation of direct and indirect energy plus the energy content of the original energy source. The net requirement is the same but neglects the energy from the original source. In the following text all reference to energy requirements will refer to gross energy requirements unless otherwise stated.

ENERGY QUALITY

Energy analysis assumes that all the energy flows within a system are comparable. However, energy flows are not all of the same type. Within an agricultural system there may be many types e.g. solar, chemical, food (Jones, 1989).

There have been arguments concerning the validity of energy analysis as a tool for testing the feasibility of a system. Some of these arguments are based upon the idea that it is not possible for a unit of electricity to be compared directly with a unit of heat. If this were true the use of EA would be limited to comparison with other analysis (Mortimer, 1991). The author of this work accepts this argument to a degree. The results from an EA are useful for comparison and can be accurate, although it is true that a comparison between differing forms of energy is inaccurate in some ways. If this is understood the results can be viewed, accounting for error, to determine validity.

METHODS OF ENERGY ANALYSIS

Boustead and Hancock (1979) give a detailed description of the methods used in most forms of energy analysis. The following text is an overview of the methods used in this research. The methods described below are for the determination of energy usage and outputs of a system; this form of analysis can be referred to as process analysis. The standardised method for process analysis is:

1. Define the system
2. Decide the objective of the analysis.
3. Chose a system boundary.
4. Identify all the inputs into the system.
5. Assign energy requirements (values) to all the inputs.
6. Identify all the outputs.

This method has significant advantages over other methods in accuracy, but has disadvantages in the fact that one must have access to considerable resources of time and data (Jones, 1989).

DEFINE SYSTEM

The definition of the system is the most important part of any energy analysis. The correct definition is important if accurate results are to be achieved. Identifying the tasks that the system sets out to achieve is the first step. Examples of tasks are production of iron plate from iron ore using method X, transport of goods Y from A to B, conversion of biomass to electricity using method Z, etc. Once the task has been defined the system must then be split into all the relevant processes.

Selecting which processes are to be included is important. A decision must be made in most cases as to which processes are relevant or significant. Not many systems have so few processes involved that all are accounted for. For instance, in a system where iron plate is being produced from iron ore does one include the process of cleaning excess dirt off the metal after transport or unloading of the plate in small quantities at its final destination? All these decisions must be taken with respect to their probable significance.

DECIDE OBJECTIVE OF ANALYSIS

The objective of any analysis must be defined so that the correct system and method is used. An analysis with the objective of looking at the energy used to produce one unit of mass will differ from an analysis based upon determining the amount of energy that a system uses to provide the service given by that product.

CHOOSE A SYSTEM BOUNDARY

The boundary is important since it determines which values are accounted for in the summation of inputs and outputs.

A boundary or virtual barrier is drawn around a system. All the processes and energy flows that stay wholly within this boundary do not contribute to the energy inputs and outputs of the system. All flows of mass or energy which cross the boundary contribute to the overall inputs and outputs of the system. Although the flows within a boundary have no direct effect on the inputs and outputs, it is important that they are understood and analysed since they will almost certainly have an indirect effect.

IDENTIFY ALL INPUTS

The energy analysis of a system involves accounting for the inputs of that system. A system is divided into component parts (procedures) and the processes necessary for completing these processes are associated with the correct procedure. Once the procedures have been determined, the energy and mass flows between and into each of them must be determined.

ASSIGN ENERGY VALUES TO ALL INPUTS

Once the division of processes and boundary determination have been completed, values must be obtained for the direct and indirect energy requirements of the processes involved. This can be done in three ways.

The first method is by direct measurement. In the case of road transport this means measuring directly the fuel consumption, tyre wear, maintenance, etc. This is complicated and time-consuming. For a complex system this could mean extensive testing for many processes which could be prohibitive in both cost and time.

A second method is through operator knowledge. Detailed questioning of machinery operators etc. can provide results which differ little from direct measured results, but require much less time and energy. However, these results will never be totally reliable since operator knowledge is rarely complete, and values are often inflated or deflated to show a rosier picture than actually exists.

The final method is the most used in energy analysis and involves the determination of values from available information in literature. All the figures obtainable through this method come originally from one of the above two methods. This has two main disadvantages. It is rare to be able to obtain values for the exact process under investigation and the values are often outdated (Mortimer, 1991). However the lack of experimentation, and therefore expense and time, means that this method of obtaining values is often used.

IDENTIFY ALL OUTPUTS

Using the same method as was used to determine energy inputs, all the energy outputs from the different procedures and processes must be determined.

LABOUR

There have been a number of different attempts to calculate labour inputs to a system: measures of 'lifestyle support', measures of energy requirement, measures of the marginal energy requirement of employment and the use of a zero energy cost (Jones, 1989). Each different system has its benefits and its drawbacks.

Labour is an energy input into a system and can contribute a considerable quantity to some systems. Pimentel and Pimentel (1979) showed that the energy input necessary to till one hectare by human power amounted to 1167 MJ, of which 35 MJ was attributable to machinery. This does not account for any form of energy expenditure outside work and is thus a measure of marginal energy requirement. These figures compare with a value of 2576 MJ for a small tractor of which 70 MJ can be attributed to labour.

There are other methods of accounting for labour input which would give even more significant figures. An energy requirement analysis would involve the metabolic energy required to sustain the labour force and the dependants of that labour force analogous with direct and indirect inputs of machinery.

If a system is based on high inputs of human labour then the human energy input is significant. If, however, the system relies on mechanical inputs such as the use of a tractor, the human input is considerably lower and may be considered of little significance. Even though there can be a significant input from human labour, modern energy analysis tends to neglect it. There are four reasons for this.

One of these reasons is that most of the applications to which energy analysis is applied are highly mechanical and the input from labour would be insignificant. Boustead and Hancock (1979) showed that the operator of an injection-moulding machine would consume 5 MJ per day attributable to their industrial work. This figure compares with 8,220 MJ for the machine. This means that the human energy contribution to the process is about 0.06 %, not a significant quantity. In most instances it is not worth the extra complication to achieve minimal increases in accuracy.

Another reason is that humans are the consumers of all the products of industry to which labour contributes. This would mean that there is no net output since all the goods are consumed by the work force. There are good arguments against this view, for instance Boustead and Hancock (1979) argue that since an industrial system can be viewed in terms of functions rather than physical components, the production by humans can be separated from the consumption and should be included.

The third and possibly the most convincing reason in industrial systems is that humans will exist whether or not they are employed in an industry, agriculture or any other manner. Thus they would consume energy anyway (Casper *et al.*, 1975). If the system being investigated was an agricultural system with high amounts of human labour, it is arguable that a worker would consume much more in a day than his non-working counterpart (Jones, 1989). Fluck (1981) calculated that the value for employment-generated energy requirement was 594 MJ per day in the USA. This difference is marginal. Until we have reached a stage of industrial efficiency where we are switched off when not producing or consuming, then there is no point is accounting for the energy contributed to a system by labour.

There is one last reason why labour might be considered in a system. The values usually calculated are those for physical work; these do not account for the information portion of a labour input which is of utmost importance. The information that has gone into a system has been obtained by the worker in a way which has inevitably consumed energy. At this point, the debate on labour reaches its esoteric extreme.

There are few systems producing energy from biomass in the UK which will not involve a large degree of mechanisation and industrialisation for economic reasons and as a result labour is not considered in this work.

LAND

In most energy analysis land is considered a free input with no associated energy value. However, it is worth mentioning that this approach has some drawbacks. In systems containing some form of agricultural production, the land may have been altered so that its ability to produce a crop has been increased. This could have been done with fertilisers from the previous crop or by previous uses. If such systems were to be compared directly with systems where this had not occurred then there would be an inaccuracy in the results. Slesser *et al.* (1977) attempted to address this problem. However, it is not a common approach and would be too complicated for the present study.

METHODS OF REPRESENTING THE RESULTS OF ENERGY ANALYSIS

Once data have been collected for the relevant processes and the calculations done, a method must be used to make sense of the results and display them in a useful and understandable manner. The data produced by an analysis are usually in the form of energy and mass usage and energy and mass outputs. In a biomass-to-energy system the mass inputs and outputs are only of interest in terms of their indirect associated energy. The figures of interest are therefore the energy in and energy out data. Using these data it is possible to provide a number of methods of display.

ENERGY RATE OF RETURN (ERR)

Since the 1970s energy analysts have been using the term energy ratio (ER) to represent the outputs from EA. This represents the ratio of energy out to the energy in. In analysis where the product is energy there are other terms for the same ratio: the most common being energy rate of return (ERR), Equation 1., and energy return on investment (EROI) (Gingerich and Hendrickson, 1993). In this text the term ERR is used. The ERR is one of the simplest ways of representing the results.

$$\text{ERR} = \frac{\text{Summation of all energy outputs from the system}}{\text{Summation of all energy inputs to the system}} \tag{1}$$

This calculation gives a number that represents the ability of a system of energy production to produce more energy than it uses. Any value greater than 1 shows that the system is capable of producing more energy than it uses, any value less than 1 shows the opposite. If the value is above 1 it does not automatically make a system a worthwhile investment.

ENERGY REQUIREMENT

The energy requirement is used in many forms of energy analysis where the output is not necessarily going to be to an energy carrier (Figure 2). It relates to the amount of energy necessary to produce a quantity of output.

$$\text{Energy requirement} = \frac{\text{Summation of all energy inputs to the system}}{\text{summation of all energy ouputs from the system}} = \frac{1}{ERR} \tag{2}$$

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CHAPTER 6

ENERGY ANALYSIS OF SMALL-SCALE SHORT ROTATION COPPICE-WILLOW BIOMASS-TO-ENERGY SYSTEMS

INTRODUCTION

Using the theory described in Chapter 5 it is possible to undertake an energy analysis of the biomass-to-energy systems being studied in this work. These systems involve the production of biomass and the conversion of this biomass into a useable form of energy i.e. electricity or heat. There are many different ways in which this may be done. It is not the purpose of this chapter to investigate all the methods possible and derive a methodology for each one; this would be an unnecessary and time consuming process. It is, however, possible to create a methodology that is unspecific enough to be portable between different methods. This chapter describes the construction of a formal structure that can be applied to biomass-to-power systems in general.

DEFINING A SYSTEM

In the most general sense the definition of the system is 'the production of useful energy from biomass' but as it stands this definition is too general. Although it is not possible to define the form of energy or biomass and retain the portability of the methodology, it is possible to divide the system into a number of component parts in order to simplify it. The use of these simplifications makes the methodology marginally less portable, but considerably more useful.

All biomass-to-energy systems share a number of processes or component parts. These components can be divided into groups which perform a function. These groups will be referred to as procedures. Examples of such procedures are storage of fuel, transportation and decommissioning. Procedures such as planting, harvesting or transportation will exist regardless of the layout of a scenario, crop or conversion method. This is helpful in defining a system which can be used to study more than one type of scenario.

The biomass-to-energy systems to be studied in this work can be divided into eight procedures. These are Establishment, Management, Crop Yield Determination, Harvesting, Transport, Storage, Conversion and Decommissioning.

PROCEDURES

The following section details each of the eight procedures individually. Each section describes the system to be investigated for analysis of the proposed Short Rotation Coppice (SRC) willow, 30-kWe, downdraft gasifier scenario (Scenario 1) described in Chapters 1,3 and 4.

ESTABLISHMENT

Most biomass-to-energy systems will involve the establishment of the crop that yields the biomass. An exception would be a system based on managing or destroying an existing woodland or crop. As with nearly all crops, establishment of biomass crops involves preparation of the ground and then planting or sowing.

Scenario 1: The establishment of a crop is critical to its continued productivity. Preparation of the ground before planting is as important as planting. SRC-willow will give a much higher yield if there is enough soil water content and little competition from other plant species. To achieve this the land should be ploughed and possibly harrowed. This produces a fine tilth, which aids water retention in the soil. Applications of foliar acting herbicide prior to planting reduces the amount of weeds, which would provide competition (Parfitt, 1995). If this weed control regime is not successful, a contact herbicide can be applied to weeds using a knapsack spray during the summer.

The crop itself is planted in the form of cuttings approximately 25cm in length, which are pushed 90% of the way into the ground. At present the favoured planting density is 10,000 per ha. Trials with different spacings have shown higher yields at higher planting densities (McElroy and Dawson, 1986), but these results were for annual harvesting, where at lower densities complete ground cover would not have been achieved. Based on this research and some other trials with longer harvesting cycles McElroy and Dawson concluded that 20,000 per ha planting density gave the best yield. Spacing of the cuttings is dependent on the proposed method of harvesting. If the crop is to be harvested by hand then there is little restriction. Spacing the cuttings at 1-metre intervals is preferred by many (Armstrong and Johns, 1997). However, if a mechanical method of harvesting, like a converted forage harvester, is to be used, then spacings of 1.25,0.75,1.25 metre are preferred.

Clone selection is dependent on individual sites. Monoclonal plantations have been common in the past, but research into polyclonal plantations suggests they may give higher yields than monoclonal plots (Dawson and McCracken, 1995).

MANAGEMENT

All crops, or plantations, need to be managed during their lifetime. A biomass crop such as *Miscanthus* or SRC-willow may need to be sprayed for insects or weeds. Established woodland may need to be thinned to maintain its efficiency and workability. Some crops or plantations may also require application of fertiliser to maintain acceptable yields.

Scenario 1: Weed growth can cause drastic reduction in yield so the control of weeds throughout the lifespan of the plantation is vital. After each harvest, the crop can be over-sprayed with a foliar-acting or contact herbicide before the stools have resprouted.

Pests and diseases can also have a significantly adverse effect on yield. Pests can be treated with insecticides at establishment or after each harvest although economic constraints usually prohibit such action (McCracken and Dawson, 1997). Similarly, diseases such as *Melampsora* (rust), which could be treated with fungicides, fall under the same economic constraints.

The use of specific clones that are resilient to pests and diseases, biological control, the use of polyclonal plantations (Dawson and McCracken, 1995) or cultural techniques provide the best ways of combating such problems.

The use of fertiliser has been shown to increase productivity in SRC-willow (McElroy and Dawson, 1986) although the increase was not significant. The crop has been seen as a low input crop in the UK and fertiliser use is almost non-existent.

CROP YIELD DETERMINATION

Determination of the crop yield is necessary for an accurate representation of a biomass system. If the yield could not be determined, it would be impossible to calculate the quantities of energy that could be produced from the harvested crop. The quantity of yield is not only of importance to the calculation of the potential quantity of energy produced, it has much further-reaching effects. The amount of machinery necessary, the size of buildings required and many other variables are dependent on the yield. The inputs to a system are as much affected by the quantity of yield, as are the outputs.

HARVESTING

The method of harvesting, the time of year, etc. are all dependent on the type of crop that is grown, the local practices and the environment. A machine used to harvest an arable crop in the summer, on hard ground, may not be suitable for a crop harvested in the winter on wet land. All biomass-to-energy systems must have a component that allows for the collection of the crop from the production site (field or plantation) and transportation to the site where it will be used. The method by which this procedure is undertaken affects the rest of the system. For example, the form in which the fuel is produced by the harvesting processes determines the method of storage and preparation.

Scenario 1: Harvesting of willow and poplar coppice has traditionally been done by hand. This laborious process produces bundles of stems, which can then be used, as cuttings, in the basket manufacturing industry or as a fuel. If the crop were to be used as a fuel it would be hand-fed to a chipper which would produce a suitable fuel. The development of SRC-willow as a fuel crop has seen the development of mechanical harvesters; these come in two forms:

Stem harvesters. These, as in hand harvesting, produce bundles of stems (Neale and Reed, 1992). This form of harvesting has two benefits. The first is when the crop has a dual purpose (for instance the production of cuttings and the production of fuel). Stems in excess of the requirements for cuttings can be chipped to provide a fuel. The second benefit is that the bundles of stems can be stored outside on the field margins where they will lose some of their moisture without significantly deteriorating, thus relieving some of the storage and drying costs. Stems stored in this way dry to a point suitable for use as fuel in a boiler system without need for further drying (McElroy and Dawson, 1986; Jirjis, 1995). The stem-dried wood, which has a lower moisture content than wood at harvest, also requires less energy to chip (Matthews *et al.*, 1994). However, the harvesting of stems in bundles is laborious. Stem harvesters take approximately 1 day per ha and chipping is similarly time-consuming. This could prove energetically and economically unfeasible if the crop was purely for energy production.

Straight to chip harvester. There are a number of designs available at present. The most favoured are based around modified forage harvesters. Claas have designed a header for their Jaguar range of forage harvesters, which can harvest 1 ha per hour of SRC-willow and turn it straight into high quality wood chip (Claas UK Ltd, 1996). There are rival designs. Maskliner have a tractor-mounted ('bender') design with similar performance, but producing a very different type of wood chip. Handling and transporting this chip is much easier than with stem bundles and the time and energy costs are lower.

However wet wood chip must be handled with care and constant aeration or turning is necessary to avoid spontaneous combustion (Nellist *et al.*, 1993).

TRANSPORT

After the crop has been harvested, it is often necessary to transport the biomass material to the site where it will be used. Often in a small scale system transport would not be necessary since the material would be carried straight to storage from harvest by tractors used during the harvesting procedure. If the distances are larger, bulk carriers may be necessary. Biomass fuel tends to have a low energy density; this means that transportation of the fuel can have serious implications for the energy analysis of a system.

STORAGE

In most cases the biomass fuel will not be in a suitable condition for use as it arrives from harvest. The fuel will need to be stored and used over a period of time. Storage methods are dependent on the form of conversion and the form in which the biomass arrives. If the conversion method requires a low moisture content fuel (e.g. gasification) and the fuel has high moisture content (e.g. SRC willow ≅ 50%) then the fuel must be dried in some way. Not only may the moisture content of the fuel need to be modified, but also, in many cases other preparatory tasks must be carried out on the fuel. If the biomass crop was SRC-willow and it had been harvested using a stem harvester, then the biomass could arrive at storage in bundles of stems. These could not be used as fuel in most conversion methods. The stems would have to be comminuted and then stored. In some cases the conversion method requires the fuel to be a certain size. In this case it may be necessary to grade the fuel. These operations will usually involve some form of mechanical process.

Scenario 1: The storage and drying of wood chips is probably the most under-researched area in biomass-to-energy systems. However, two main processes will probably be adopted:

Aeration without the use of added heat. Wet wood chip poses many problems. Left to itself it will be attacked by fungi and bacteria (Jirjis, 1995), and subsequent handling of the fuel is thus made dangerous as the airborne spores can pose health problems. As decomposition takes place heat is produced (Nellist *et al.*, 1993) and this heat can, in some circumstances, lead to the combustion of the wood chip which not only destroys the fuel but can be very dangerous. To avoid these processes, air can be forced through the wood chip; this reduces the temperature, thus reducing the growth of fungi and bacteria and the risk of combustion. Forcing ambient air through the wood chip also has the effect of reducing the moisture content (Nellist *et al.*, 1993), although this can take a long time and be energy intensive.

Drying with heated air. This process again relies on forcing air through the wood chip. Air moisture can be removed from the mass of wood chip by heating the air much faster than if the air is at ambient temperature. This lessens the problems of fungi and bacteria growth and as a result the temperature of the chips can be controlled and the danger of combustion alleviated. This process uses more energy in the same amount of time but uses less energy per unit of removed moisture than drying with ambient air (Nellist *et al.*, 1993).

CONVERSION

Once the fuel has been grown, harvested and prepared it must be converted into the required form of energy. Methods of conversion have a number of things in common. They consume fuel, biomass and possibly some gas or electricity to run ancillary systems, and they produce energy in a useable or more useable form than the fuel being converted. Conversion methods are covered in Chapter 2 in general and Chapter 3 for scenario 1.

DECOMMISSIONING

At the end of a system's lifespan one must consider the processes necessary to return the land, machinery etc. to its previous, or another useful, form. In the case of the land the crop must be removed and whatever agricultural operations necessary to return the land to a normal state must be undertaken. Machinery must be dismantled and any collections of waste material must be disposed of.

Scenario 1: There has been little research into the decommissioning of SRC-willow as the lifespan of a plantation is approximately 20 years and the interest in SRC-willow as a large-scale energy crop has not been around for that long. Unlike many crops SRC-willow leaves stools behind which have to be dealt with. There are three approaches to doing this.

1. Grubbing up. This is probably the most time-consuming and energy-intensive method. It involves the use of a large digging machine to remove the stools from the ground after which the stools need to be disposed of.
2. Kill the stools with a contact herbicide such as glyphosate, then deep-plough the ground to expose the stools and destroy their root network. Then collect the broken stools.
3. Stools would be sprayed with a contact herbicide and then left. After this the land can be sued for grazing or a heavy disker or rotovator used to break up the stools.

DECIDE THE OBJECTIVE OF THE ANALYSIS

The purpose of the analysis in this work is to investigate the feasibility of small-scale energy production from biomass. The results could also be used to compare biomass-to-energy systems with other energy production technologies, enabling a more informed assessment of the practicality of implementing such systems. A number of different indicators can be used to do this. The most common is the Energy Ratio (ERR). This indicator needs only a sum of energy inputs and outputs. This defines the type of analysis that is necessary: an analysis based upon the summation of the energy inputs and outputs. This, however, is not the ideal situation. Providing the user with an output of just two numbers would severely limit the scope for optimisation and investigation of the system.

A second requirement should be placed upon the system requiring it to investigate the sensitivities of the output to changes in important parameters. The system should also be capable of giving information on the specific forms of energy used in the total sum.

To do this the analysis must be made more detailed and have a much wider depth in its calculations than if the output was just a ratio of energy in to energy out.

DETERMINING THE BOUNDARY OF AN ENERGY REPRESENTATION OF A BIOMASS-TO-ENERGY SYSTEM

The determination of a boundary is critical to the accuracy of the energy analysis of a system. In a biomass-to-energy system there are many inputs and all of these must be accounted for if they cross the boundary. It is therefore important that the boundary is clearly drawn.

Earlier in this chapter the division of processes into procedures was discussed. Each of the procedures remains in the boundary, as do all the transactions which go on between the procedures. For example, if the heat involved in drying the fuel prior to conversion comes from the conversion method it is deemed a transaction between two procedures and as such stays within the boundary. This transaction should not be ignored, it must be investigated since it will undoubtedly affect other inputs and outputs, but since it does not cross the boundary it will not contribute to the energy in or energy out summations.

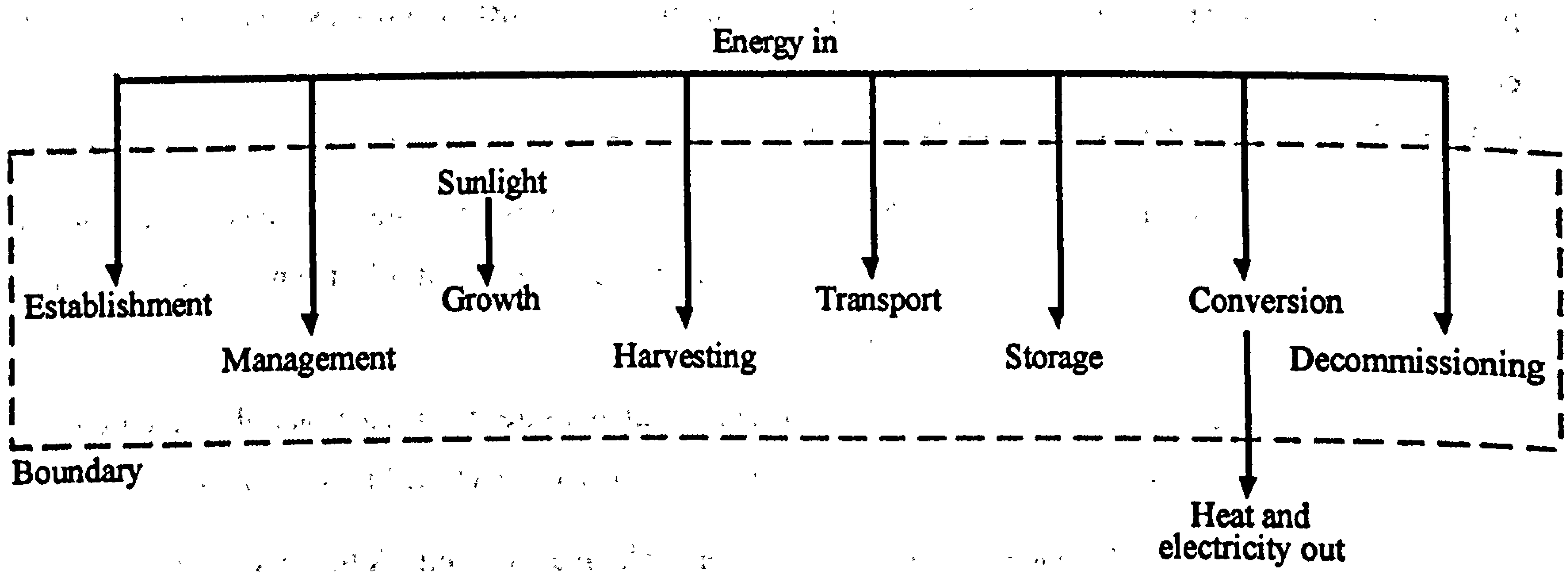

Figure 1. Schematic of biomass-to-energy system, showing the boundary.

Processes that consume fuel and power or materials in some way (where that power, fuel or material does not come from one of the other processes) must import this fuel or power or material from outside the boundary. Not all the processes which input energy and goods into a system will need to be accounted for. Solar energy is a major input into the biomass system. In conjunction with minerals within the soil etc. this contributes to the growth of the biomass crop. These energy inputs can be considered as free. Sunlight will fall on the land area whether there is a crop there or not. The only effect that the system has on incident sunlight is to increase the quantity used, not to affect the amount that is incident on the land. It is disputable whether or not minerals from the soil are a free input. The minerals within the soil that are taken in by the biomass crop are not necessarily replaced and therefore the quality of the land may decrease. However, attempting to account for the energy value of minerals in the soil would become too complicated. It would also lead to a representation, that is not comparable with most other representations of agricultural systems. The boundary drawn for this work is shown in Figure 1.

IDENTIFY ALL INPUTS

A list of processes which might be carried out in a biomass-to-energy system was compiled. This is not a completely comprehensive listing but represents the processes that are most commonly used and have a significant input. Not all of these processes may be used by a specific component.

Table 1. List of processes and the functions associated with them.

Process	Necessary functions
Short distance transport	Tractor and trailer
Spraying crop	Tractor and sprayer
Applying fertiliser to crop	Tractor and fertiliser applicator
Ploughing land	Tractor and plough
Harrowing land	Tractor and harrow
Rotavating land	Tractor and rotovator
Planting crop	Tractor + planting machine or self propelled planter
Harvesting crop	Self propelled harvester or tractor-harvester
Chipping crop	Stand-alone chipper or tractor-chipper
Movement of crop within storage	Storage handling machinery
Digging ground	Mechanical digger
Transportation by road	Large or small truck
Transportation by rail	Railway stock and network
Conversion into energy	Conversion machinery
Drying of biomass fuel	Drying infrastructure

The list of processes was composed from practical experience of systems and through extensive literature research (Foster, 1993; Mitchel *et al.*, 1995; Nellist *et al.*, 1993; Mitchell, 1994; Bhatia *et al.*, 1993; Christersson, 1993; Gingerich and Hendrickson, 1993; Grado and Strauss, 1993; Jirjis, 1995; Sonnino, 1994; Stjernquist, 1994; Szego and Kemp, 1973; Turhollow, 1994; Zingale, 1996). From these descriptions it is possible to determine which processes are necessary for different systems. The list is given in Table 1.

Many of the processes listed above also have a mass component associated with them. A list of material inputs was also made. They are: Herbicide, Pesticide, Fertiliser, Willow cuttings, Fencing, Storage building and Conversion building.

There has been a simplification with both processes and materials. There are many different forms of plough and tractor combination and conversion machinery. Similarly there are varieties of fertiliser and herbicide. These variations have been accounted for in the analysis.

ASSIGN ENERGY REQUIREMENTS (VALUES) TO ALL INPUTS

Assigning values to the energy inputs of a system is the most crucial task in producing accurate results from an energy analysis. Methods for determining the values have been discussed in Chapter 5. The determination of values by direct measurement has been impossible for most of the processes that the model uses. The exception to this is the gasification machine, which has been researched at LARS. The rest of the necessary inputs have been determined by a combination of figures collected from literature and operator surveys. The calculations and values used are dealt with in Appendix 1.

IDENTIFY ALL OUTPUTS

As it was necessary to identify all the inputs that had a significant effect, it was also necessary to identify all outputs. This process is usually much simpler than for inputs as outputs are by nature more condensed. In most situations the outputs can be refined down to physical waste, electricity and heat. These three forms of energy or embodiments of energy are present in most energy production systems.

The necessity to account for each output in the analysis is dependent on what the conversion system, and its products, are being used for. If a system is producing waste material with a high-energy content this could be accounted for as an energy output. However if this waste is being dumped, as is usually the case, then it is not a useful output.

Measurement of electrical output of machines is simple since nearly all generators have a system for measuring output. Heat is similarly measured in many systems.

Some direct measurements have been taken on the 30-kWe downdraft gasifier at LARS and the results are detailed in Chapter 4. Information on other machines has come from manufacturers and machinery operators.

IMPLEMENTATION OF ANALYSIS

The analysis for feasibility of biomass-to-electricity systems was implemented in a mathematical model. This model was used to develop a computer model; the Biomass Energy Analysis Program (BEAP).

INTRODUCTION

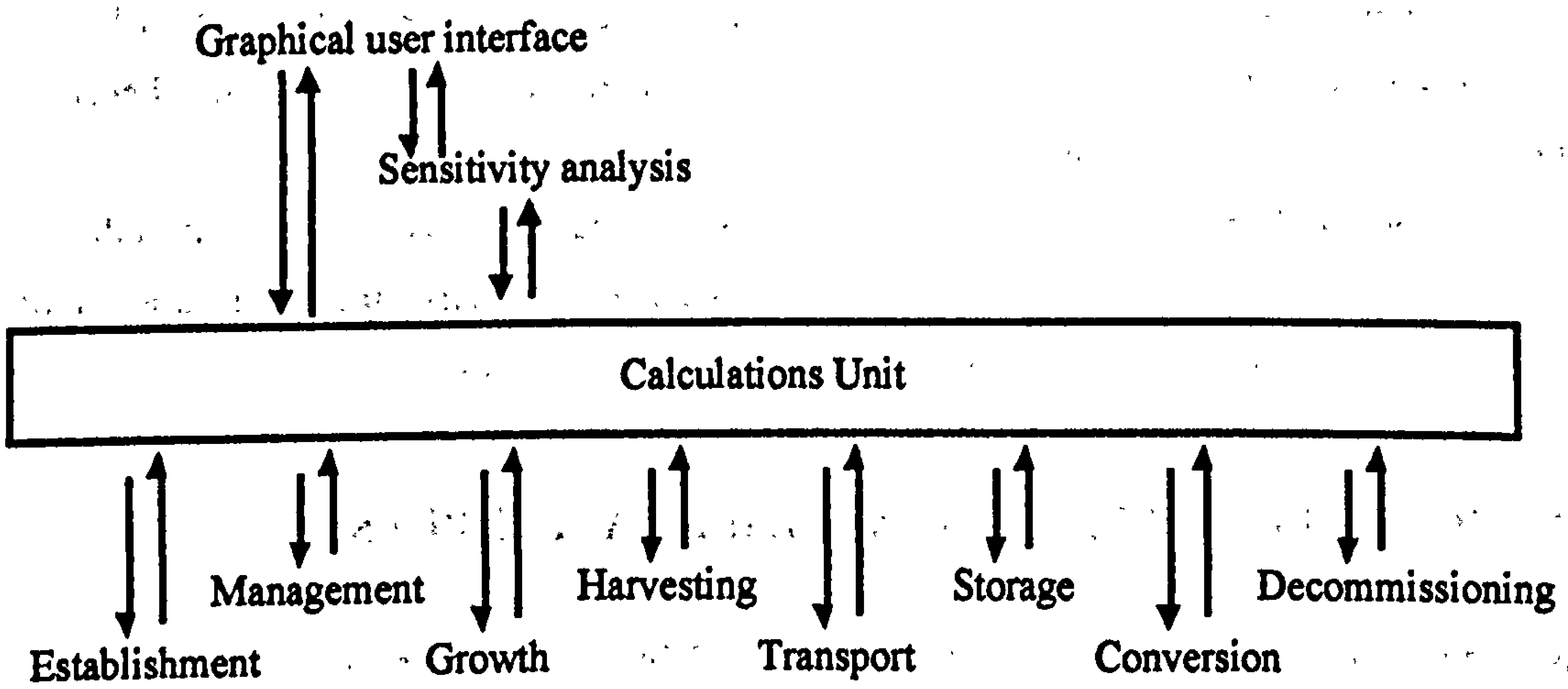

Figure 2. Schematic of processes in BEAP.

The BEAP program was developed using DELPHI; a visual programming language based on Pascal. This visual language allows the model to have a user-friendly interface allowing prospective energy producers as well as academics to use it. The interface allows access to two major routines: the energy rate of return calculation unit and a unit enabling sensitivity studies to be performed. A schematic representation of the model is shown in Figure 2.

CALCULATION UNIT

The calculation unit contains a number of subroutines, which calculate values of energy usage. For each individual year in the lifespan under consideration the calculation unit uses subroutines to calculate energy usage for each procedure.

There is a separate subroutine for each of the normal procedures i.e. establishment, management, harvesting, transport, storage, conversion and decommissioning. Each of these subroutines imports and exports the relevant data needed for its calculations to and from the other subroutines.

ESTABLISHMENT

The establishment subroutine is a good example of the basic code used to operate all the other subroutines. In addition to the calculations of indirect and direct energy for standard operations, it calculates indirect inputs from agrochemicals and the willow cuttings planted.

MANAGEMENT

The management subroutine determines whether or not management operations are to be carried out during the year in question. It must then calculate energy usage of standard operations and agrochemical use.

CROP MODEL

In the absence of a computer-based link to the crop modelling done using the LARS-willow model, this subroutine takes an inputted value of yield for the year in question. Yields while the crop is establishing itself are lower than achievable yields later in its life; this subroutine makes calculations to correct for this.

HARVESTING

The harvesting subroutine calculates energy usage of standard functions used in harvesting, for instance; harvesting machine, chipper (if used) and tractor and trailer for transport on-farm. The routine also calculates the quantity of harvested biomass in wet tonnes per ha. The calculation allows for a loss factor to be associated with the harvesting procedure although this loss factor is usually very low.

TRANSPORT

The transport subroutine calculates energy use by transport operations depending on the weight and volume of fuel, distance and method of transportation.

STORAGE

Within the storage subroutine, as well as calculations for standard functions and infrastructure, the calculations for energy use in drying have been split. The subroutine can calculate for two-stage cooling-drying, direct drying and drying without the use of energy. The subroutine also calculates the quantity of biomass fuel after storage, dependant on required moisture content and losses associated with the drying method (due to biological degradation).

Conversion

The conversion unit calculates the energy usage associated with the conversion machinery and infrastructure. It calculates the optimum number of machines for available quantity of biomass, based on inputted criteria. The subroutine also calculates the total energy output i.e. the heat and electricity that the conversion machine can deliver from the quantity of fuel.

Decommissioning

This subroutine calculates the energy used by standard functions and agrochemical usage.

Sensitivity Unit

The sensitivity unit allows for calculations of ERR for an individual year or a selected lifespan carried out while a particular variable is changed. This can establish the sensitivity of the system to certain changes e.g. the sensitivity of the overall ERR to changes in the distance that the fuel must be transported from the farm to conversion.

The sensitivity routine works by modifying the variable in question and then using the calculation unit and its subroutines to calculate the ERR and energy usage.

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SHORT ROTATION COPPICE WILLOW CROP MODELLING

INTRODUCTION

One of the major influences on the energy, or economic, feasibility of a biomass-to-energy system is the quantity of biomass which can be produced, per ha, from the cropping area. Therefore determination of the useful yield of a biomass crop is vital in any analysis.

To analyse the biomass-to-energy systems examined in this thesis, knowledge of the SRC-willow yields for different sites within the UK is necessary. There have been several SRC-willow trials whose intention has been to determine yields (Mitchell *et al.*, 1995; Parffit, 1997; Carter, 1996; Stevens, 1996). Some of these have given yields lower than might be expected. These trials have been limited in their geographical scope and have used established clones that do not represent the higher yielding varieties now available.

To fill geographical gaps left by yield trials and to provide a tool for future analysis, a mathematical model of biomass growth would be a powerful tool. This chapter describes the work undertaken developing the LARS-Willow model (Evans *et al.*, 1996) to produce a tool for modelling willow yields for multiple years' growth.

Work on the LARS-willow model had been started by Evans et al. previous to the work undertaken in this thesis. Problems with the code of this model and the lack of development to allow for multiple years' growth meant that a significant quantity of work was necessary to develop the model.

The aim of this modelling work was to determine a value for potential SRC-willow yield for locations around the UK. This information was then used to determine geographical influences on the feasibility of SRC-willow-to-energy systems within the UK. The model was also used to determine if there was an optimum rotation period for yield and whether this optimum rotation period varied with location. Information on rotation period and yield is useful in determining the management regime of plantations and the effects on feasibility.

The accuracy of modelled yield relies on the input data, which are predominately weather data. The yield may vary considerably from year to year. If the yield for a specific rotation period is to be investigated this could lead to a sizeable variation in the results. Consequently a suitable time period over which to investigate the system must be chosen and yields over this period averaged. The predicted lifespan for machinery and plantations is approximately 20 years. Therefore, where enough weather data was available, yield was averaged over a period of 20 years. In places where less data were available a period as close to 20 years as possible was used.

UNITS OF BIOMASS YIELD

The moisture (water) content of biomass fuels varies considerably at harvest. The moisture content of a grass crop like Miscanthus at harvest can be as low as 20 % (Bullard and Kilpatrick, 1997). This is less than the moisture content of SRC-willow at harvest which is approximately 50 % (Parfitt, 1995; Jirjis, 1995; Nellist, 1993). The ability of a biomass fuel to produce energy is related to its moisture content (Herendeen and Brown, 1987), so comparing harvested weights of different biomass sources is not advisable. As a result of varying moisture contents, the quantity of biomass is usually expressed in terms of oven-dry tonnes per hectare per year (odt.ha^{-1}yr^{-1}). In many cases this measure gives a good indication of the quantity of biomass available for energy production, however, its usefulness is dependent upon the method of conversion.

When SRC-willow is harvested it is usually after leaf fall and the odt.ha^{-1}yr^{-1} value takes account only of the stem biomass that has been harvested. In contrast, when *Miscanthus* is harvested approximately 30 % is in the form of leaves (Bullard *et al.*, 1997). The leaves may not be suitable as a feedstock to many forms of conversion and therefore an odt.ha^{-1}yr^{-1} value, in this case, could be misleading.

THE LARS-WILLOW MODEL

The LARS-Willow model was initially developed in 1996. The model is based upon the SIRIUS wheat model and the WIGO willow growth model (Evans *et al.*, 1996). It models the biological processes in willow production. The model derives a yield for willow biomass for a single year given input data for maximum and minimum temperature, solar radiation and precipitation for each day of the year.

The SIRIUS wheat model, on which a lot of the processes within the model were based, calculates growth dependant on soil water and nitrogen limitation as well as temperature and solar radiation. These units were included in the original LARS-Willow model although the calibration work carried out (Evans *et al.*, 1996) on the model disabled these.

Because this work considered potential production the soil, water and nitrogen limitation modules of the model were not required and it was necessary to remove these sections from the model and to modify the routines to work in this way. Once these modifications had been made it was necessary to check the calibration again. The results of this re-calibration were satisfactory.

The model was not capable of calculating yields for growth periods of more than one year. This is a problem when modelling a plant usually grown in rotations of two or more years.

Growth for an individual year is obviously affected by the accumulated biomass of the previous year so calculating one individual year's growth was a limitation which had to be overcome. The model was modified to carry over accumulated biomass and for calculations of variable lifespan. This significant modification allowed calculation of results necessary to determine the feasibility of systems based on multiple year rotation coppice willow.

CHOICE OF LOCATIONS FOR INVESTIGATION

Locations for modelling were chosen to give a wide range within the UK. However the suitability of land for biomass production, independent of weather limitations, varies considerably within the UK. Scotland has a limited suitability for large-scale biomass production since much of the available land is too marginal and of poor quality. Similarly, the investigation of biomass production within areas where most of the land is highly productive arable land could be considered not worthwhile, especially now that the allocation for set-aside has been cut to 5% from 15% (MAFF, 1997).

All these non-weather considerations needed to be looked at and the investigation of a wide range of sites allows for changes in land use and political will. As a result an even spread of sites over the entire UK was chosen (Table 1).

Table 1. List of sites chosen for modelling of SRC-willow yield giving information on site and availability of weather data.

Site	Location (Lat., Long.)	Altitude (m)	Yrs for which data are available
Auchincruive	55.48 , -4.57	45	1960-62
Cardiff	51.42 , -3.35	67	1960-71,73-81
Drummond Castle	56.33 , -3.88	113	1962-81
Edinburgh East Craigs	55.95 , -3.32	61	1962-81
Eskdalemuir calculated	55.32 , -3.20	242	1960-68,72-74,77-79,88-93
Eskdalemuir measured	55.32 , -3.20	242	1960-68,72-74,77-79,88-93
Everton	50.73 , -1.57	16	1962-81
Fortrose	57.58 , -4.08	5	1963-74
Gatwick	51.15 , -0.18	59	1962-81
Hawkridge	51.05 , -3.60	314	1964-66,70-81
High Mowthorpe	54.10 , -0.63	175	1962-81
Hillsborough	54.45 , -6.07	116	1960-71,73-81
Keele	53.00 , -2.27	179	1962-81
Lairg	58.02 , -4.40	107	1960-62,73-81
Long Ashton	51.43 , -2.67	45	1962-81
Oxford	51.77 , -1.27	63	1962-81
Pen-Y-Fridd	53.22 , -4.15	84	1962-81
Preston Wynne	52.12 , -2.50	84	1960-74,77-82
Rothamstead calculated	51.80 , -0.35	128	1962-81
Rothamstead measured	51.80 , -0.35	128	1971-89
Santon Downham	52.47 , 0.68	24	1960-74,76-81
Slaidburn	53.98 , -2.43	192	1962-82
Terrington St Clements	52.75 , 0.30	3	1962-81
Warsop	53.22 , -1.12	46	1960-68,72-74,76-81,83-85

WEATHER INPUT FILES

The accuracy of input data is of paramount importance to the accuracy of output data. The main input data for the LARS-willow model are the weather data input files containing data for maximum and minimum temperature, precipitation, wind speed, vapour pressure and solar radiation. The LARS-willow model is purely a potential production version and has no moisture stress allowance, as a result information for vapour pressure, precipitation and wind speed are superfluous at present.

Weather information was obtained from the ARCMET database. Recordings of solar radiation are not common and only two of the listed sites had a significant quantity of recorded solar radiation data. As solar radiation is one of the primary inputs to the model another method must be found of acquiring this data.

CALCULATING SOLAR RADIATION VALUES

In the absence of solar radiation data for a site a way must be found to calculate these values as they are vital to the calculation of yield. A number of different methods have been proposed to make these calculations (Bristow et al., 1984; Rietveld, 1978; Thornton et al. 1998). These different methods use a variety of input variables to produce results for solar radiation.

Probably the most popular method for the calculation of solar radiation (to be used for input into growth models) is Rietveld's 1978 method. This relies on the sunlight hours and geographical positioning of the site.

CALCULATION OF SOLAR RADIATION BASED ON SUNLIGHT HOURS.

Using (1) to (7) (Rietveld, 1978) the solar radiation can be calculated from sunshine hours. This is not a direct conversion but an inferred value dependant on latitude.

Rad	= Solar radiation value for the day
RadA	= Angot value (radiation on the top of atmosphere) $MJ.m^{2-1}day^{-1}$
Sun	= Recorded sunlight hours
MaxSun	= Astronomical day length
xlat	= Latitude in radians
sd	= Solar declination
day	= Day of year
S	= Constant value = 1370 $W.m^{2-1}$
C	= Constant

$$Rad = RadA\left(a + \frac{b \times Sun}{MaxSun}\right) \times c \tag{1}$$

where

$$a = 0.1\left(\frac{0.24 \times Sun}{Maxsun}\right) \tag{2}$$

$$b = 0.78 - \left(\frac{0.44 \times Sun}{MaxSun}\right) \tag{3}$$

$$RadA = \left(\frac{86400}{\pi}\right) \times S \times 1.035 \times \left((h \times \sin(xlat) \times \sin(sd)) + \left(\cos(xlat) \times \cos(sd) \times \sin\left(a\cos(-\tan(xlat) \times \tan(sd))\right)\right)\right) \tag{4}$$

$$MaxSun = 24 \times \left(\frac{a\cos\left(-\tan(xlat) \times (\tan(sd))\right)}{\pi}\right) \tag{5}$$

where

$$xlat = lat \times 2 \times \left(\frac{\pi}{360}\right) \tag{6}$$

and

$$sd = 0.41 \times \cos\left(\frac{2.0 \times \pi \times (day - 172)}{365}\right) \tag{7}$$

The accuracy of the method described above is dependant on a number of constants. In his paper Rietveld calculated these constants for a wide range of locations around the world. However this work requires coefficients which give accurate results for the range of sites across the UK chosen for yield calculations. Since calibration for each site is not possible in the absence of Solar Radiation data it is necessary to produce coefficients for the whole of the UK which can be used for all the sites in this work.

To calculate a suitable coefficient two sites placed reasonably far apart but not at such extremes that the values calculated for them would be overly inaccurate were chosen. These sites were Eskdalemuir and Rothamstead (35 degrees south and 65 degrees north). The quantity of information available meant the investigation was limited to one year for each site. The years 1960 and 1969 respectively were chosen the most complete data were available for those years.

Using the measured data for these years and the calculations above, a value for the coefficient (C) was calculated at 0.68. This value gives the most accurate results for the combined sites.

Values for calculated and measured solar radiation are shown in Figures 1 and 2. The values obtained for calculated solar radiation show a very good correlation with the measured values.

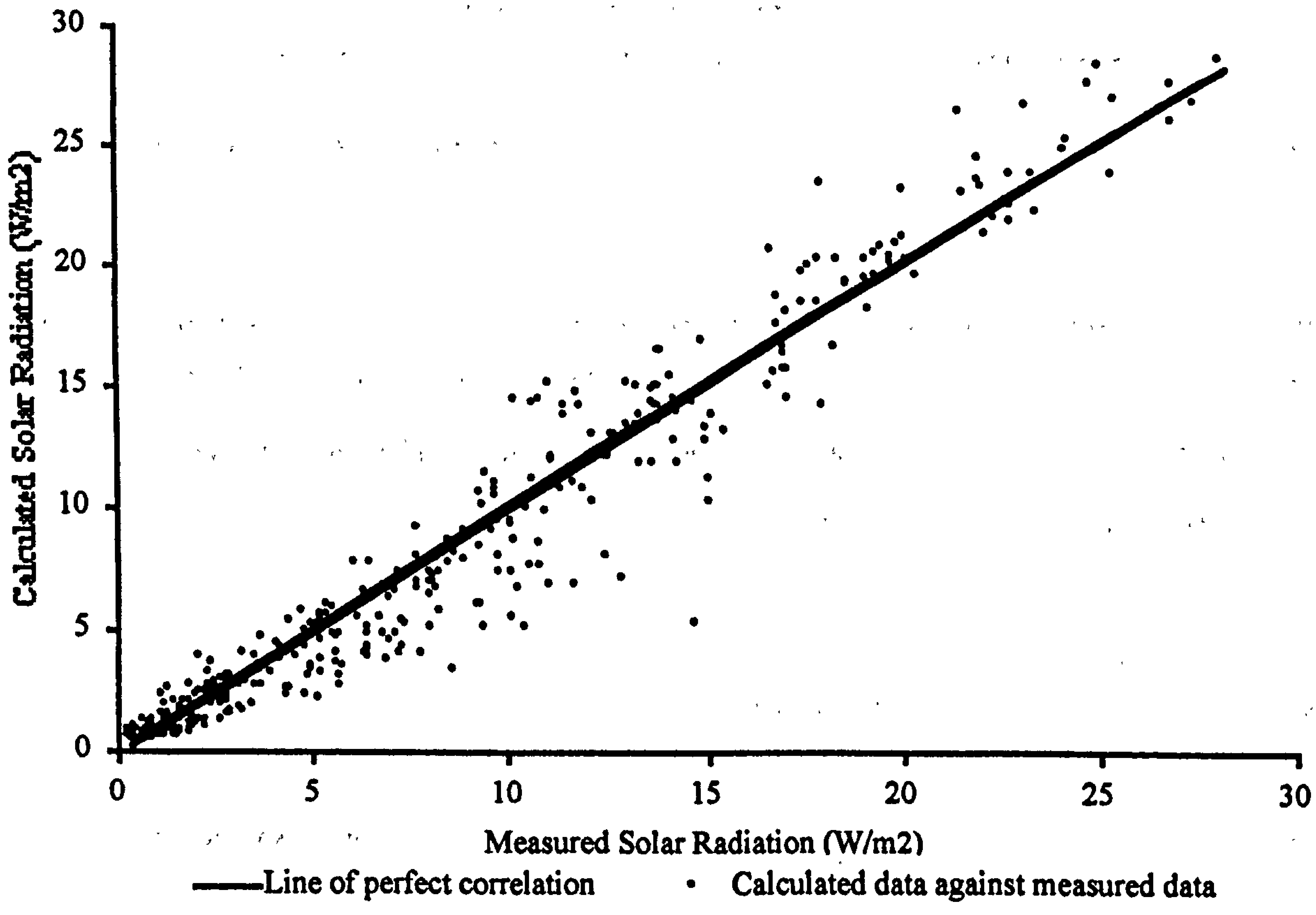

Figure 1. Measured and calculated solar radiation data for Eskdalemuir 1960 using Rietveld's 1978 method.

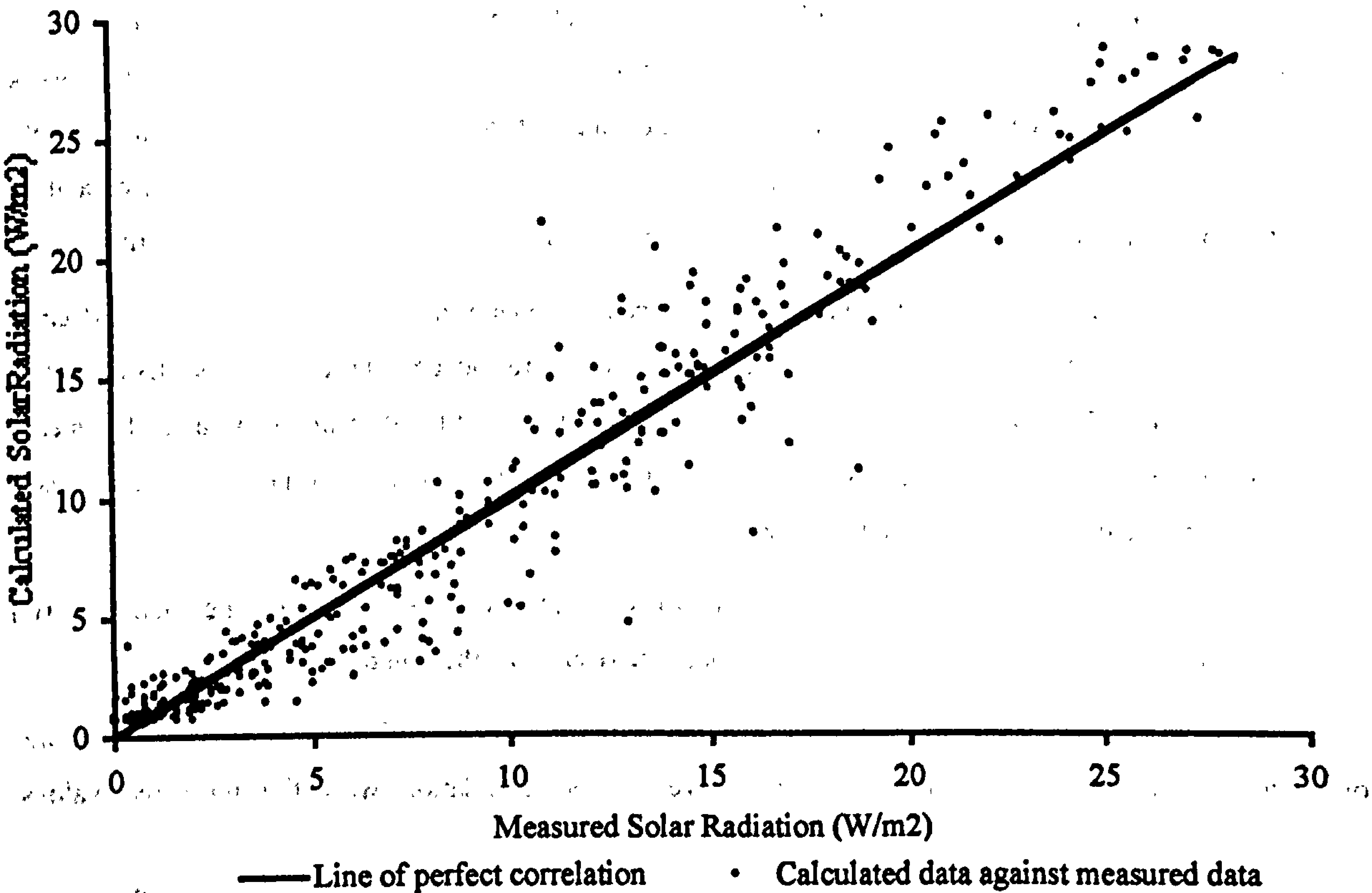

Figure 2. Measured and calculated solar radiation data for Rothamstead 1969 using Rietveld's 1978 method.

CALCULATION OF SOLAR RADIATION FROM MAXIMUM AND MINIMUM TEMPERATURES

In the absence of sunlight hour data a different method of calculation must be used to obtain solar radiation data. This method could lead to a larger number of sites being suitable for yield calculations.

Bristow and Cambell (1984) developed a method for calculating Solar Radiation in this way.

Tt = daily total atmospheric transmittance
A = empirical coefficient
B = empirical coefficient
C = empirical coefficient
ΔT = daily range of air temperature
ΔTM = monthly mean range of air temperatures
Q_0 = daily extraterrestrial insolation (J/m^{-2})
Rad = Solar Radiation for the day
S_o = Solar Constant (1360 Wm^{-2})
Dm/d = Mean value of distance from earth to sun / distance from earth to sun (this value can be assumed to be unity since it never varied more that 3.5% from unity).
ϕ = latitude of location
δ = Solar Declination (the equation no. 7 from the previous method can be used to calculate this)

$$T_t = A(1 - \exp(-B\Delta T^C)) \tag{8}$$

$$Tt = \frac{Rad}{Q_0} \tag{9}$$

$$Q_0 = 86400 S_0 \left(\frac{dm}{d}\right)^2 (h_s \sin\phi \sin\delta + \cos\phi \sinh_s) / \pi \tag{10}$$

$$B = 0.036 \exp(-0.154 \Delta TM) \tag{11}$$

Bristow and Campbell describe a number of methods of calculating ΔT. These different methods are used to create more accurate results in the sites used in their study. These methods are

$$\Delta T = T_{max} - T_{min} \tag{12}$$

$$\Delta T(J) = T_{max}(J) - (T_{min}(J) + T_{min}(J+1)) / 2 \tag{13}$$

Where J is the Julian Day No.

The third method uses the ΔT value calculated from equation 13 and modifies it dependent on the state of precipitation. For a rainy day ΔT is reduced by 25%, and if the previous day has a ΔT of less than 2 degrees of that of the day before that then its value is also reduced 25%.

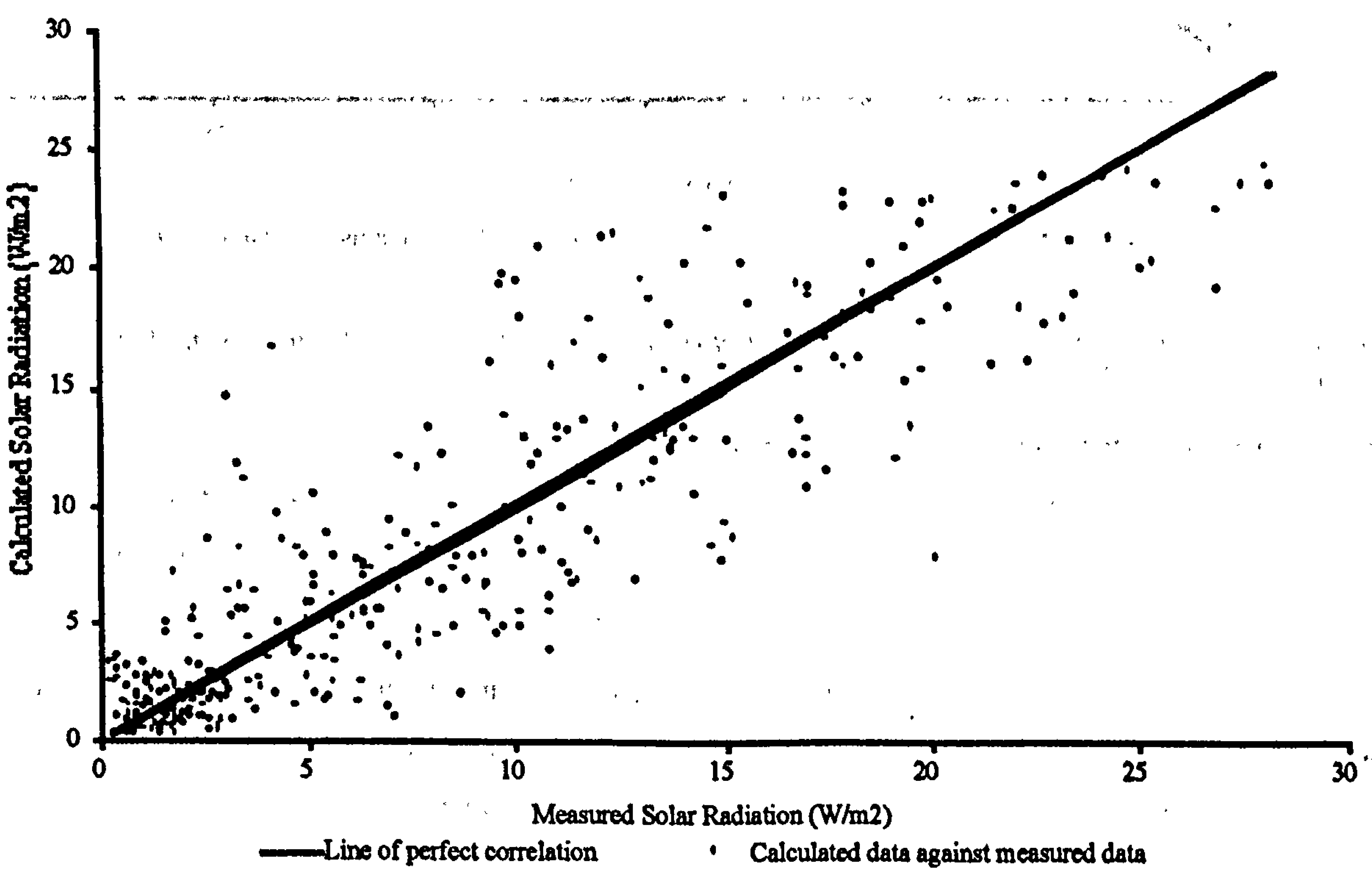

Figure 3. Measured and calculated solar radiation data for Eskdalemuir 1960 using Bristow and Campbell's 1984 method.

Using the same sites (Eskdalemuir 1960 and Rothamstead 1969) as in the Rietveld method values for A and C were derived which gave minimum error for both sites. These values were 0.575 and 2.25 respectively.

The calculations were done for all three of the ΔT methods described above. It was found that the values for ΔT derived from equation 5 were the most accurate. This is probably due to a number of reasons. The sites used in Bristow and Campbell's calculations are for inland locations in the US. The airflow and temperature variations in an area like this are probably very different from the locations we have chosen within the British Isles. The results of the most accurate method are shown in Figures 3 and 4.

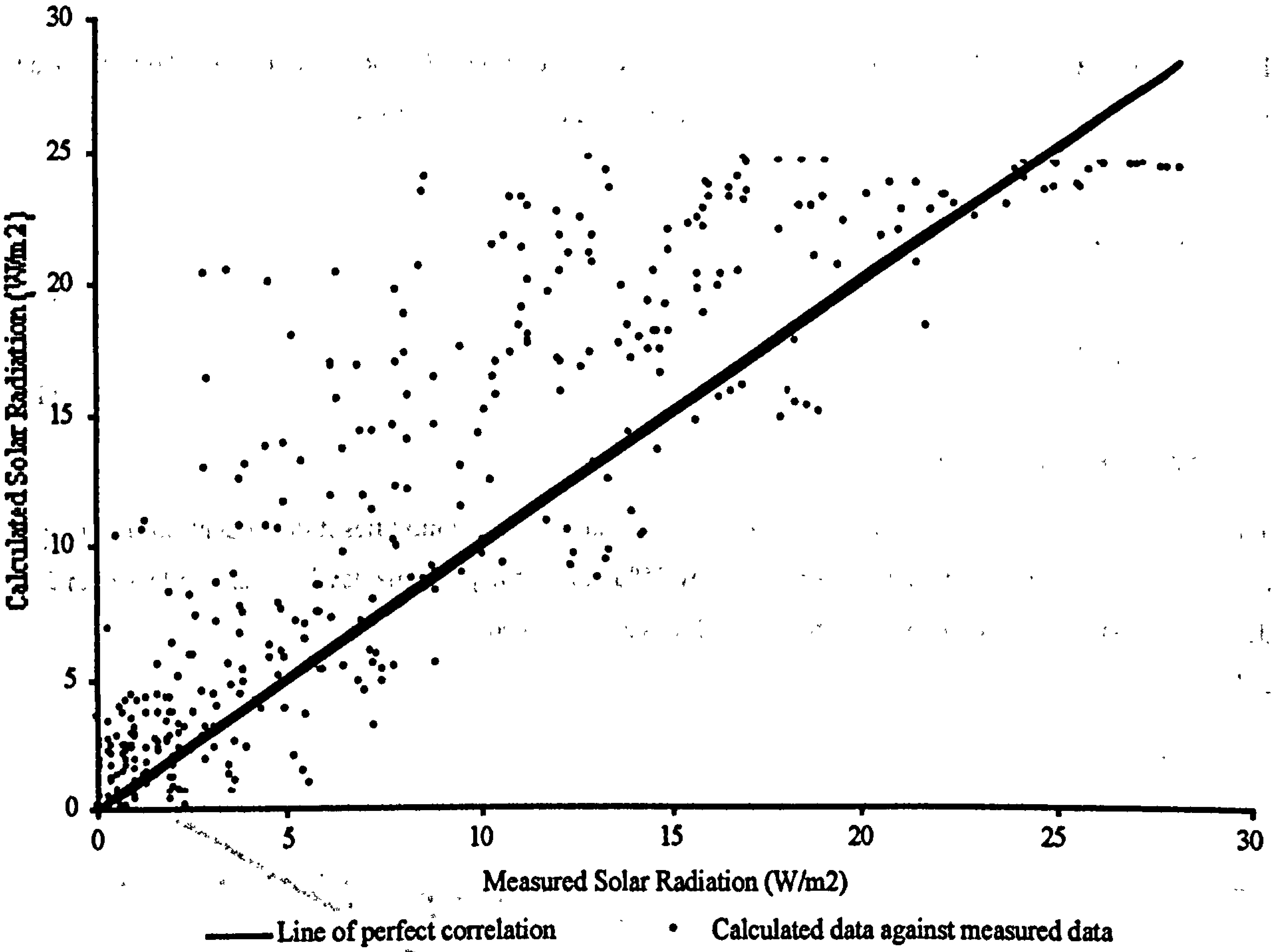

Figure 4. Measured and calculated solar radiation data for Rothamstead 1969 using Bristow and Campbell's 1984 method.

CONCLUSIONS ON SOLAR RADIATION CALCULATIONS

The two methods described above give two different approaches to calculation of solar radiation. Rietveld's 1978 method gives the most accurate results of the two. This is not surprising as sunlight hours are related more directly to solar radiation than the maximum and minimum temperatures.

Since there are a wide range of sites for which sunlight hour data are available it was decided to use the Rietveld method for calculating solar radiation data for input into the yield model. This calculation was therefore applied to the range of sites described in Table 1.

The Bristow and Campbell model, although not as accurate as the other method, is however a useful tool and could be used with good results for sites where no sunlight hour data is available.

RESULTS

The calculations can be split into two sections.

1. Investigation of the effects of rotation period on yield, and from these data, the determination of an optimum rotation period or periods using selected sites.

2. The calculation of yield for the optimum rotation period or periods for all the sites.

DETERMINATION OF OPTIMUM ROTATION PERIOD

Three sites were selected (Drummond Castle, Keele and Gatwick); these sites are widely distributed in the UK and should give a reasonable spread of results. For each the average yield was calculated for rotation periods of 1 to 10 years over a 20 year period. A maximum of 10 years for the rotation period was used since this is the maximum length for which more than one period of that length will fit within the 20 year lifespan of a system. Where the rotation period would not fit exactly within the 20 year period one shorter rotation was included, e.g. for the 3-year rotation period the value is an average of the yield from 6 three year rotations and one 2-year rotation. The calculated average annual increase in harvestable biomass is listed in Table 2.

Table 2. Average annual yields for Drummond Castle, Keele and Gatwick for rotation periods between 1 and 10 years.

Rotation (Years)	Drummond Castle (odt/ha/yr)	Keele (odt/ha/yr)	Gatwick (odt/ha/yr)
1	18.48	19.76	24.92
2	19.02	20.09	25.01
3	19.24	20.17	25.04
4	19.34	20.20	25.05
5	19.35	20.26	25.08
6	19.42	20.27	25.09
7	19.47	20.34	25.07
8	19.45	20.28	25.08
9	19.46	20.33	25.09
10	19.49	20.35	25.10

From Table 2 it can be seen that the model predicts little benefit in an increased rotation period. The most common rotation period in practice is three years although this is now being changed to four years in some areas. As a result most of the machinery being developed is designed to work with stems of this age. A rotation period of three or four years also allows for a quick return on investment for the operator. For these two reasons and also considering that the increase in yield from a longer rotation is not significant, the calculations for the other sites were done for a three year rotation period.

CALCULATION OF POTENTIAL PRODUCTION FOR SITES IN THE UK

For many of the sites there was not a continuous span of 20 years for which suitable weather data were available (Table 1). In these cases calculations were done for as many rotations of three and four years as possible. The results of these calculations were averaged to give an average potential production value for yield for all the sites (Table 3). The values in Table 3 for Coefficient of Variation (CV) show that the variation in yield for the individual years is not large.

Table 3. Potential Yields for three and four year rotations for all the sites investigated.

Site	Yield for 3 yr. rotation	CV
Auchincruive	21.5	0.108232
Cardiff	24.7	0.069887
Drummond Castle	19.2	0.070422
Edinburgh East Craigs	19.4	0.079734
Eskdalemuir calculated	17.3	0.081359
Eskdalemuir measured	18.9	0.086745
Everton	26.9	0.067548
Fortrose	17.2	0.090832
Gatwick	25.0	0.07900
Hawkridge	21.0	0.084203
High Mowthorpe	19.4	0.10678
Hillsborough	19.8	0.094055
Keele	20.2	0.096083
Lairg	15.2	0.096099
Long Ashton	24.7	0.064184
Oxford	24.6	0.074177
Pen-y-Fridd	22.2	0.072231
Preston Wynne	22.8	0.085032
Rothamstead calculated	22.8	0.08444
Rothamstead measured	24.1	0.058487
Santon Downham	22.8	0.087776
Slaidburn	18.8	0.094766
Terrington St Clements	23.3	0.083805
Warsop	19.8	0.081068

MODEL VALIDATION

It must be stressed that the results obtained for yield listed in Table 3 are for potential production. There is no accounting for water or nutrient stress in the model and as a result of this simplification, the yields modelled will probably be larger than those normally achievable. Values of 12 odt.ha^{-1}yr^{-1} (Dawson and McCraken, 1995) are usually cited as the achievable norm at present.

To validate the values for yield from the model, comparison with available yield data was necessary. A number of studies have been carried out into SRC-willow yields (Mitchell *et al.*, 1995; Parffit, 1997; Carter, 1996; Stevens, 1996). These studies were usually on plots of a smaller area than would be used in a biomass-to-energy-system. The size of the plots and the experimental nature of the husbandry will usually lead to higher yields than would be available from a large-scale commercial plantation. However, improvements in management strategies and inclusion of new higher yielding clones (Lindergaard, Barker, 1997) will raise the yields obtainable in larger plantations.

Comparison with available information (Mitchell *et al.*, 1995;Parffit, 1997;Carter, 1996; Stevens, 1996) on yield shows a favourable correlation with the modelled values (Figure 5). This suggests that with good management strategies and clone selection yields similar to the modelled values can be achieved.

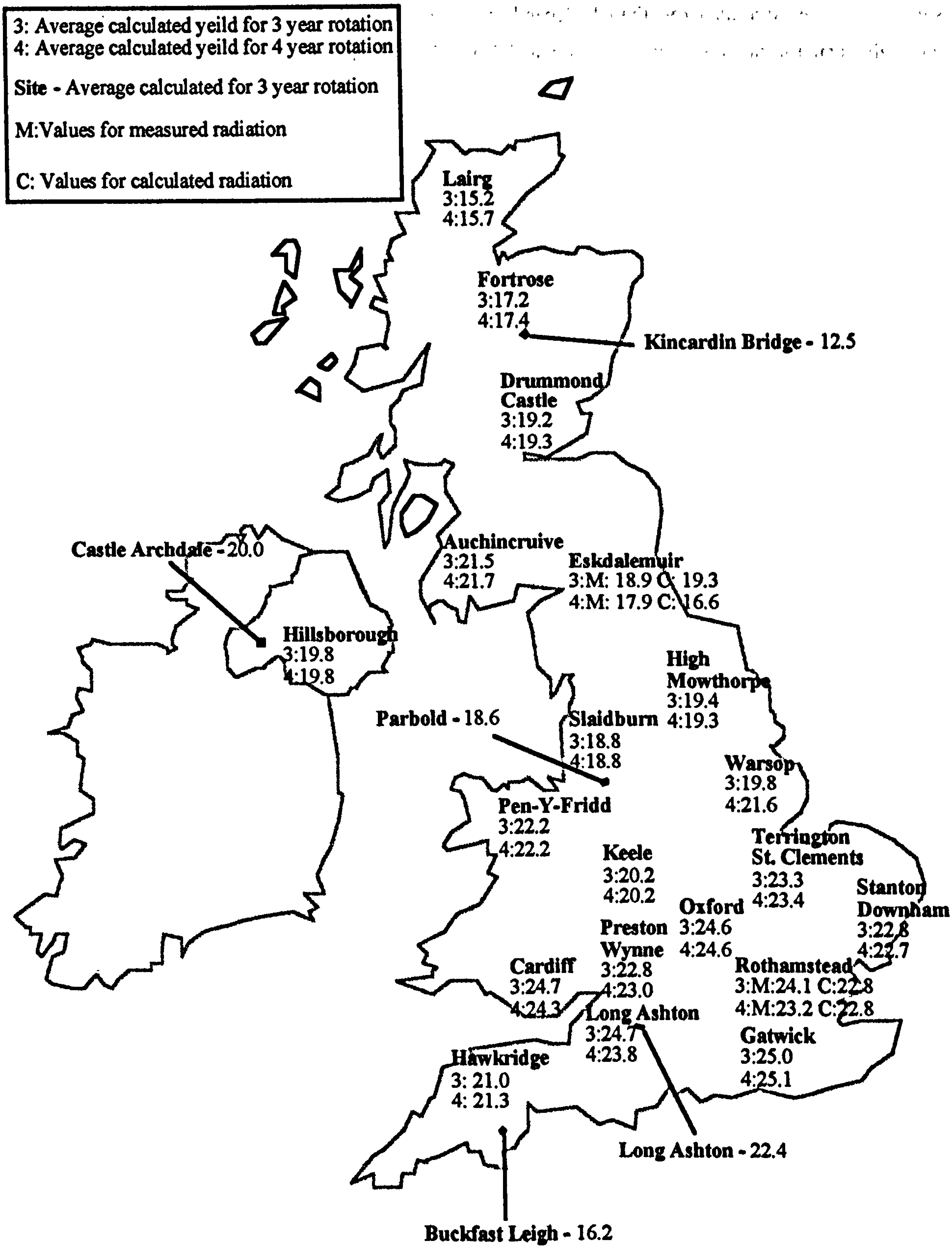

Figure 5. Map showing values for calculated yield for 3 and 4 year rotations and experimentally measured values for comparison

CONCLUSION

With the consideration of increasing yields and information obtained from the review of experimental work, the results in Table 3 are a good representation of biomass yields. The potential yield values show the variation across the UK dependent on latitude and sunlight hours. These results provide invaluable data for the investigation of the feasibility of biomass to energy systems.

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CHAPTER 8

ENERGY MODELLING RESULTS

INTRODUCTION

The Biomass Energy Analysis Program (BEAP) was validated against available data on biomass crop production. Once it was established that the model was accurate it was used to investigate in detail the proposed 30-kWe downdraft gasifier scenario (Chapters 1,3) and case studies of two other scenarios. These results not only investigate the feasibility of each, but also prove the flexibility of BEAP.

The results from BEAP are either in terms of energy usage per year and per section (establishment, management etc.) or in a value of Energy Rate of Return (ERR). The input values for energy usage of different functions and materials (Appendix 1) have three bands: low, medium and high. The medium band represents the 'best' estimate. If the banding is not specified in the text, it refers to the medium banding.

There were limited available data with which to compare the output of BEAP. Foster (1993) calculated energy rates of return for production of wood chip fuel to 'farm gate'. By modifying the inputs to BEAP to provide a similar system, a comparison of the establishment, management, harvesting and decommissioning components of BEAP was possible. Values obtained from BEAP were similar to those obtained by Foster (1993) for two of the three input criteria.

Most of the work is contained within the detailed investigation of the standard 30-kWe scenario. Two forms of storage were considered: cooling followed by drying and direct drying. Cooling-drying proved to be much more energy-intensive than direct drying. Cooling-drying leads to Energy Rates of Return (ERRs) of less than half those for drying. This investigation showed that with potential yields (Chapter 7) ERRs are between 15 and 27. These results are favourable and would indicate a system that is energetically feasible.

Further investigation of the 30-kWe scenario looked at the sensitivity of the ERR to changes in five variables: area, moisture content at harvest, lifespan, percentage of year operating and transport distance. The results of this sensitivity study show that the ERR will drop significantly with decreases in yield (and therefore increases in area) and transport distance. The sensitivity analysis also shows that increases in lifespan beyond 20 years do not make a large difference to the ERR. They also show that the ERR of the system is surprisingly robust to changes in the percentage of the year in which it is operated.

Using the predicted potential yields from the crop modelling (Chapter 7) and BEAP, a risk assessment was done for the 30-kWe scenario at different geographical locations. This risk assessment showed that the predicted variations in yield from the crop model would not significantly affect the achievable ERR. More than 50% of the locations achieved an ERR of 17, or greater, 100% of the time; over 90% of the sites achieved an ERR of 15, or greater, 100% of the time.

VALIDATION OF BEAP MODEL

There has been little similar research into energy rates of return for biomass-to-energy systems based upon SRC-Willow biomass. Foster (1993) arrived at values for energy ratios (equivalent to ERR) for producing SRC-willow biomass to the 'farm gate'. These values do not include conversion to electricity or transportation, so a comparison is only valid up to the point prior to conversion although she did include decommissioning.

Table 1. Summary of parameters for comparison with analysis by Foster (1993).

Variable	Value
Agrochemicals	No fertiliser
Harvester	Claas forage harvester
Lifespan	21 years
Rotation period	4 years
Available area	1 ha
Yield	8 $odt.ha^{-1}yr^{-1}$ in first year, 12 $odt.ha^{-1}yr^{-1}$ subsequently

The range of agricultural operations that Foster used in her work is not fully specified, so a comparison of her data against data from BEAP using standard agricultural operations was deemed suitable. A summary of the important parameters for the analysis is shown in Table 1.

A value of 17 $MJ.kg^{-1}$ for wood chip was calculated, assuming that wood is utilised at a moisture content of 15% and the calorific value of dry wood is 20 $MJ.kg^{-1}$ (Matthews *et al.*, 1994). This value was used to determine the energy content of the wood at the 'farm gate'.

The values from BEAP are divided into high, low and medium estimates based upon input values for energy usage. Similarly, the results from Foster (1993) are divided into low, best and high. It is important to understand that the system stays the same in these bands, and that only the input values for energy usage change. Comparison of results is shown in Table 2.

Table 2. Comparison of results from BEAP model and analysis by Foster (1993).

BEAP output		Foster, (1993)	
Band	Energy Ratio	Band	Energy Ratio
Low	20.47	Low	20.8
Medium	21.29	Best	29.9
High	21.85	High	61

From Table 2, it can be seen that the results from BEAP compare favourably with Foster's results in the bands low and medium/best. The comparison for the high values however, is less favourable. This is most probably a result of differences in the input data. Detailed investigation narrowed the variations in input data for BEAP between the low medium and high input data. The input values for Foster's analysis are not discussed in her paper but, from her results, it is possible to assume the values used for the high set of inputs vary considerably from those for low and best. This is probably the cause of the discrepancy. A variation of approximately 7% for the values produced from BEAP is considered by the author to be preferable to the variation of 200%, shown by the results of the Foster analysis.

Although there is a discrepancy in the high banding, the similarity of the results in the low and medium/best banding shows that the BEAP model and the results from Foster's analysis are comparable.

DETAILED INVESTIGATION OF 30-KWE SCENARIO

A standard system was needed to investigate the feasibility of small-scale systems. Chapters 1 and 3 detail the selection of a farm-based system based around a 30-kWe downdraft gasifier. The available area used in the scenario is based upon the predicted yield for each site (Chapter 7). A brief description of the processes used in the scenario follows.

A 20 year lifespan was chosen; this is a good estimate of plantation lifespan. This assumes that the machinery used solely by the 30-kWe scenario can also function for this period. A three year rotation is justified, since at present a three year rotation is the accepted practice and there is no significant change in potential production for a longer i.e. four year rotation (Chapter 7). A detailed list of the input variables for the analysis can be found in Appendix 2.

Establishment. The area would be prepared using a plough and harrow and planted using a step planter designed specifically for planting SRC. The planting density would be 10,000 ha^{-1}. A slow release herbicide would be used to control weeds in the first year.

Management. Herbicide would be used after each harvest, so that each of the sub-areas would be treated every 3 years.

Harvesting. Harvesting would be done with a forage harvester with a special SRC header. Damaged stools would be trimmed by hand. The chip produced by the forage harvester would be collected directly into trailers.

Transport. The conversion and storage facilities would be sited within tractor and trailer distance of the crop, so that no extra transport would be necessary.

Storage. Chips would be stored in a barn and kept cool, by passing air through a ventilated floor, and then dried or dried immediately from point of harvest in a large drying barn.

Conversion. Conversion would be done using a 30-kWe downdraft gasifier based upon the system discussed in Chapter 3.

Decommissioning. The stools would be sprayed with herbicide after harvest and left to rot until spring when they would be rotovated into the ground.

Two forms of fuel preparation were investigated throughout the analysis: these are cooling followed by drying or direct drying. However the cooling-drying option gave significantly lower values for ERR, because it used much more energy. Therefore, more emphasis has been attached to the direct drying results.

GEOGRAPHICAL FEASIBILITY STUDIES

The sites chosen for the potential yield prediction work (Chapter 7) were investigated to give an ERR value based on the 30-kWe system and potential yields.

Since yields vary and the scenario only needs a set quantity of material per annum there will be an optimum area for any site dependent on the yield. This area will produce enough fuel to operate the system and minimise overproduction. To determine this area, the sensitivity of ERR to yield for a number of different areas was investigated (Figures 1 and 2, for drying and cooling-drying respectively). In Figure 1 there is a noticeable knee at the point were there is overproduction of the wood fuel.

For drying, this set of results was used to arrive at an optimum area for maximising ERR. These optimum areas are shown in Table 3. Included in Table 3 are optimum values for yields of 10, 12, 14, 16, 18 and 20; these yields were included to show the range of values obtainable with lower than potential yields.

Table 3. Calculated optimum areas for sites investigated.

Site	Average calculated yield (odt.ha^{-1}yr^{-1})	Optimal area (ha)
Auchincruive	21.5	9
Cardiff	24.7	8
Drummond	19.2	10
Edinburgh	19.4	10
Eskdalemuir Calculated	16.4	12
Eskdalemuir Measured	18.0	11
Everton	27.0	7
Fortrose	17.2	11
Gatwick	25.0	8
Hawkridge	21.0	9
High Mowthorpe	19.3	10
Hillsborough	19.8	10
Keele	20.2	9
Lairg	15.2	12
LARS	25.1	8
Oxford	24.5	8
Pen-y-Fridd	22.2	9
Preston Wynne	23.2	8
Rothamstead Calculated	22.8	8
Rothamstead measured	24.1	8
Slaidburn	18.8	10
Stanton Downham	22.8	8
Terrington St Clements	23.3	8
Warsop	21.3	9
yield 10	10	19
yield 12	12	16
Yield 14	14	14
Yield 16	16	12
Yield 18	18	11
Yield 20	20	9

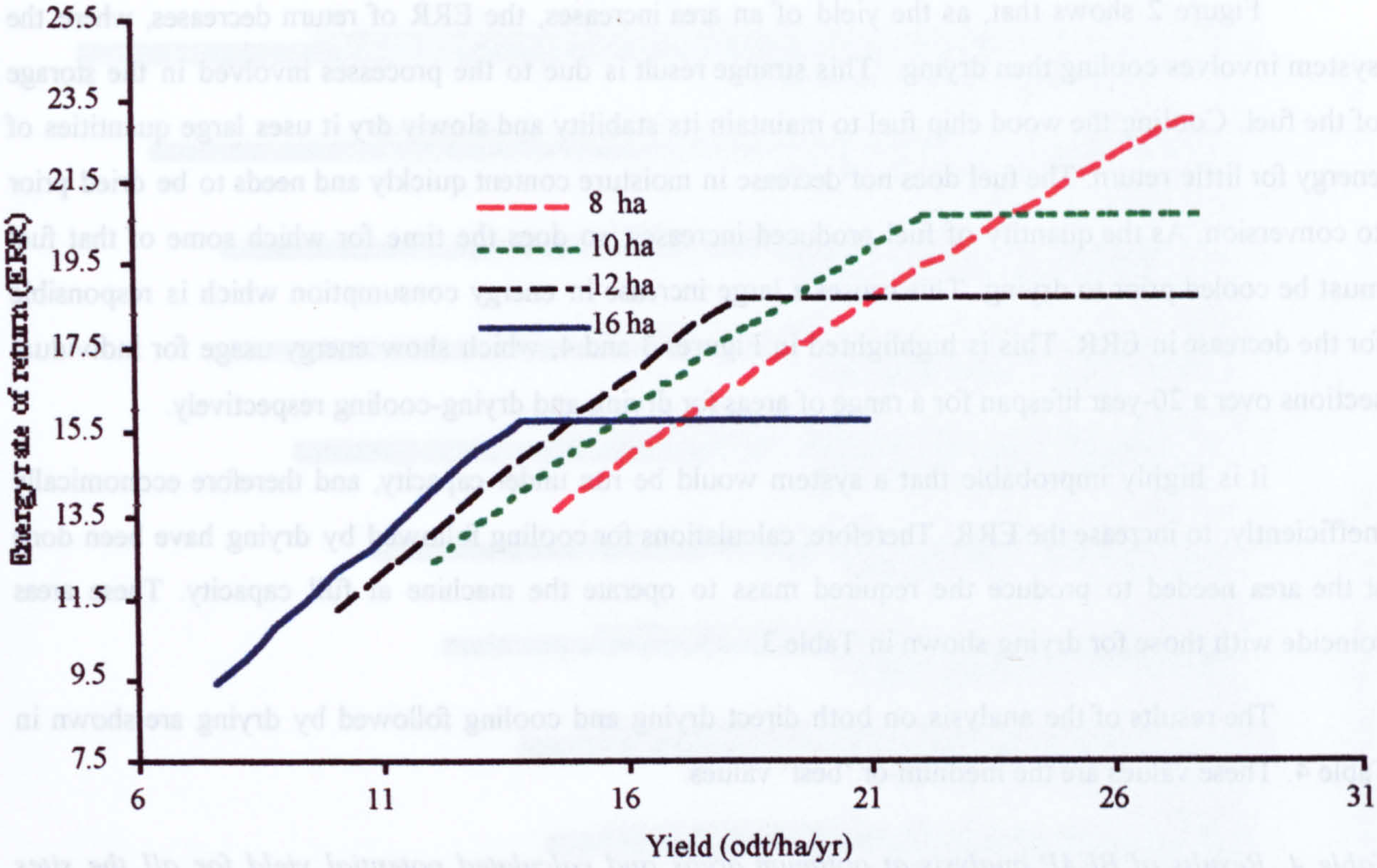

Figure 1. Sensitivity of energy rate of return to changes in yield for drying for a range of crop areas

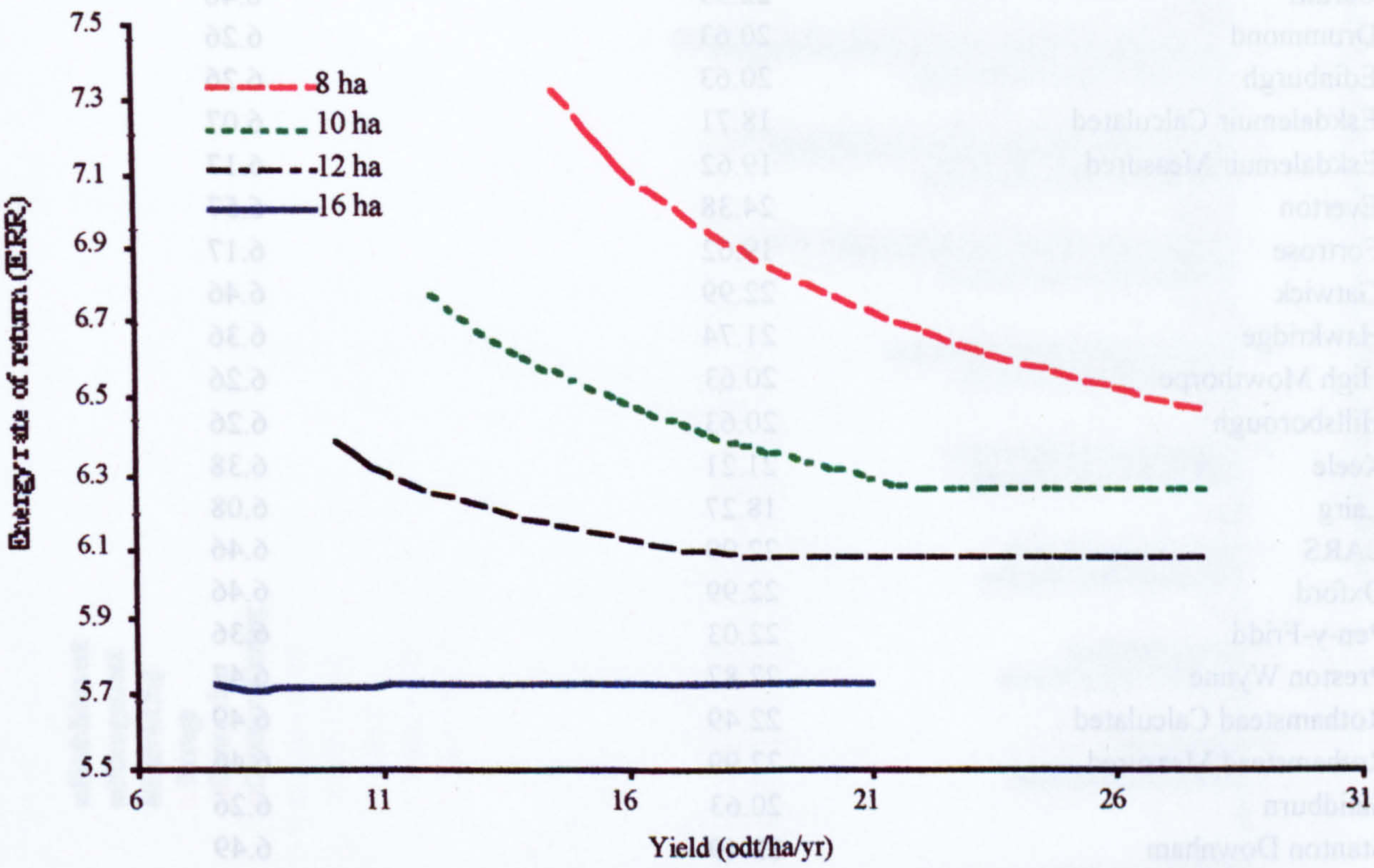

Figure 2. Sensitivity of energy rate of return to changes in yield for cooling followed by drying, for a range of areas

Figure 2 shows that, as the yield of an area increases, the ERR of return decreases, where the system involves cooling then drying. This strange result is due to the processes involved in the storage of the fuel. Cooling the wood chip fuel to maintain its stability and slowly dry it uses large quantities of energy for little return. The fuel does not decrease in moisture content quickly and needs to be dried prior to conversion. As the quantity of fuel produced increases, so does the time for which some of that fuel must be cooled prior to drying. This causes a large increase in energy consumption which is responsible for the decrease in ERR. This is highlighted in Figures 3 and 4, which show energy usage for individual sections over a 20-year lifespan for a range of areas for drying and drying-cooling respectively.

It is highly improbable that a system would be run under-capacity, and therefore economically inefficiently, to increase the ERR. Therefore, calculations for cooling followed by drying have been done at the area needed to produce the required mass to operate the machine at full capacity. These areas coincide with those for drying shown in Table 3.

The results of the analysis on both direct drying and cooling followed by drying are shown in Table 4. These values are the medium or 'best' values.

Table 4. Results of BEAP analysis at optimum areas and calculated potential yield for all the sites under investigation.

Site	ERR for calculated yield for drying	ERR for calculated yield for cooling followed by drying
Auchincruive	21.74	6.36
Cardiff	22.99	6.46
Drummond	20.63	6.26
Edinburgh	20.63	6.26
Eskdalemuir Calculated	18.71	6.07
Eskdalemuir Measured	19.62	6.17
Everton	24.38	6.57
Fortrose	19.62	6.17
Gatwick	22.99	6.46
Hawkridge	21.74	6.36
High Mowthorpe	20.63	6.26
Hillsborough	20.63	6.26
Keele	21.21	6.38
Lairg	18.27	6.08
LARS	22.99	6.46
Oxford	22.99	6.46
Pen-y-Fridd	22.03	6.36
Preston Wynne	22.87	6.47
Rothamstead Calculated	22.49	6.49
Rothamstead Measured	22.99	6.46
Slaidburn	20.63	6.26
Stanton Downham	22.49	6.49
Terrington	22.87	6.47
Warsop	21.74	6.36
yield 10	14.11	4.83
yield 12	15.77	5.73
yield 14	17.11	5.89
yield 16	18.71	6.07
yield 18	19.62	6.17
yield 20	21.05	6.39

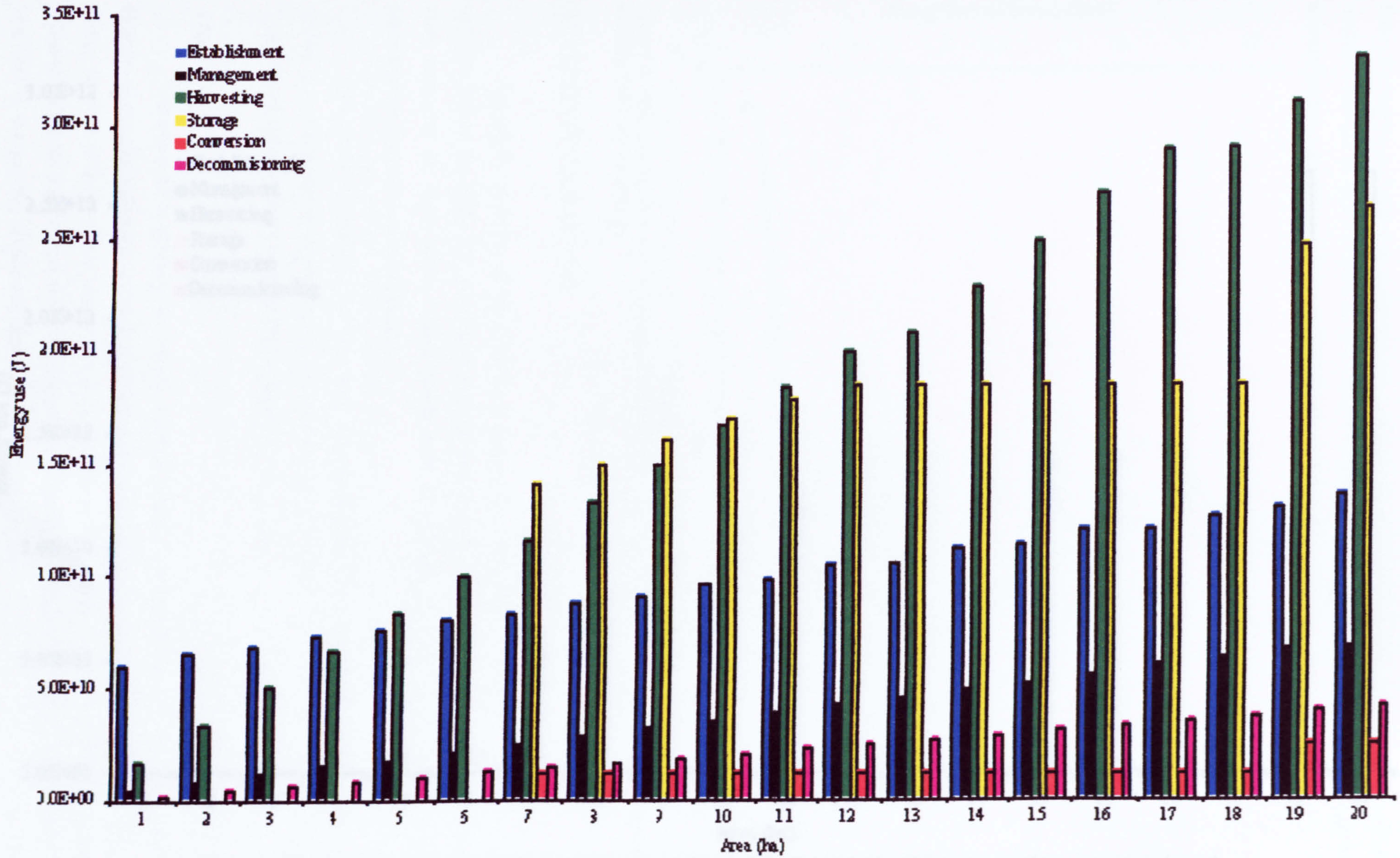

Figure 3. Energy usage by section for a 20 year lifespan for drying (yeild is optimum and transport usage is zero)

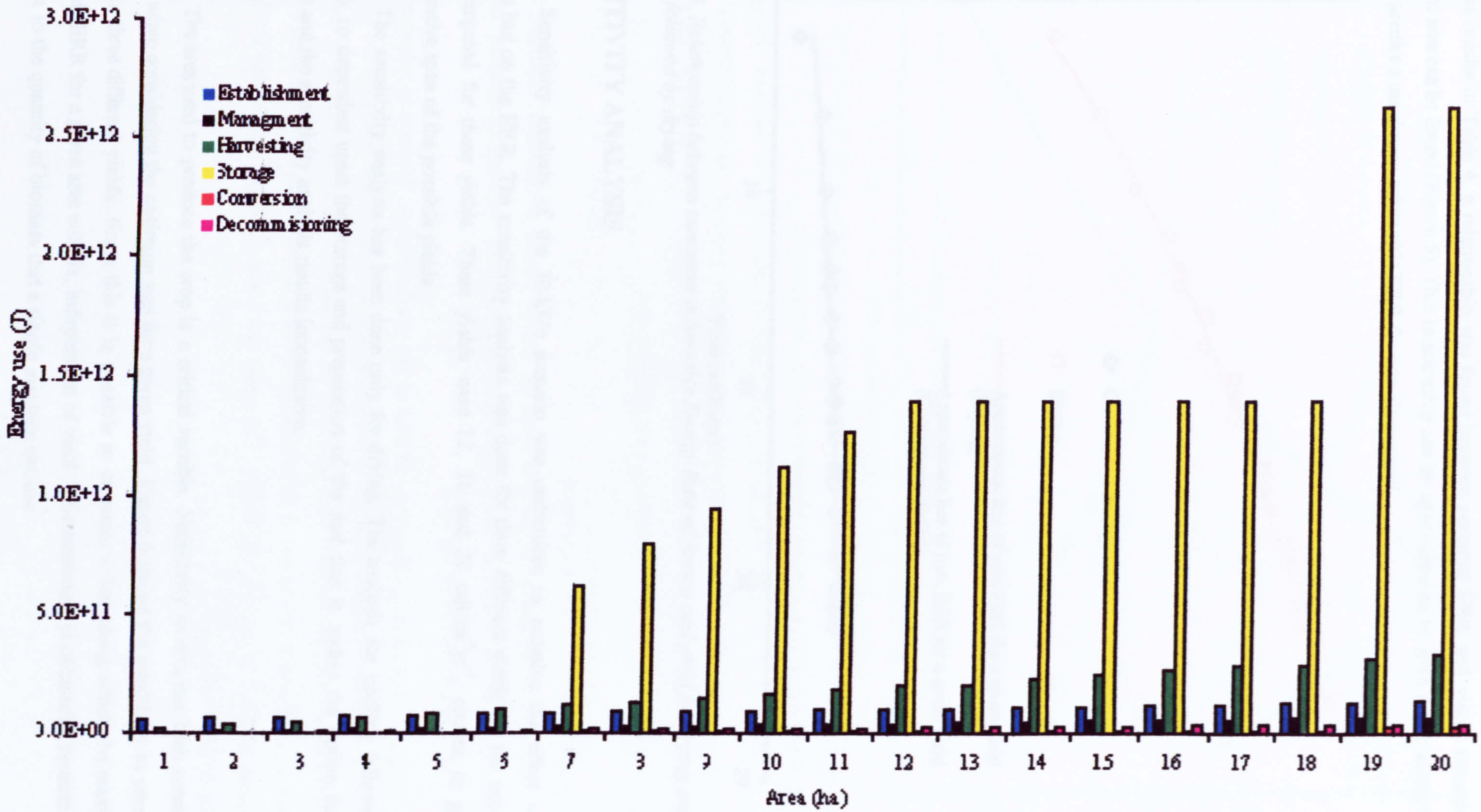

Figure 4. Energy usage by section for a 20 year lifespan for cooling followed by drying (yield is optimum and transport usage is zero)

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From the results in Table 4, a relationship was found between potential ERR and yield, assuming an optimum area can be found (Figure 5). This relationship can be approximated to give a line along which one can predict a maximum achievable ERR for any given yield.

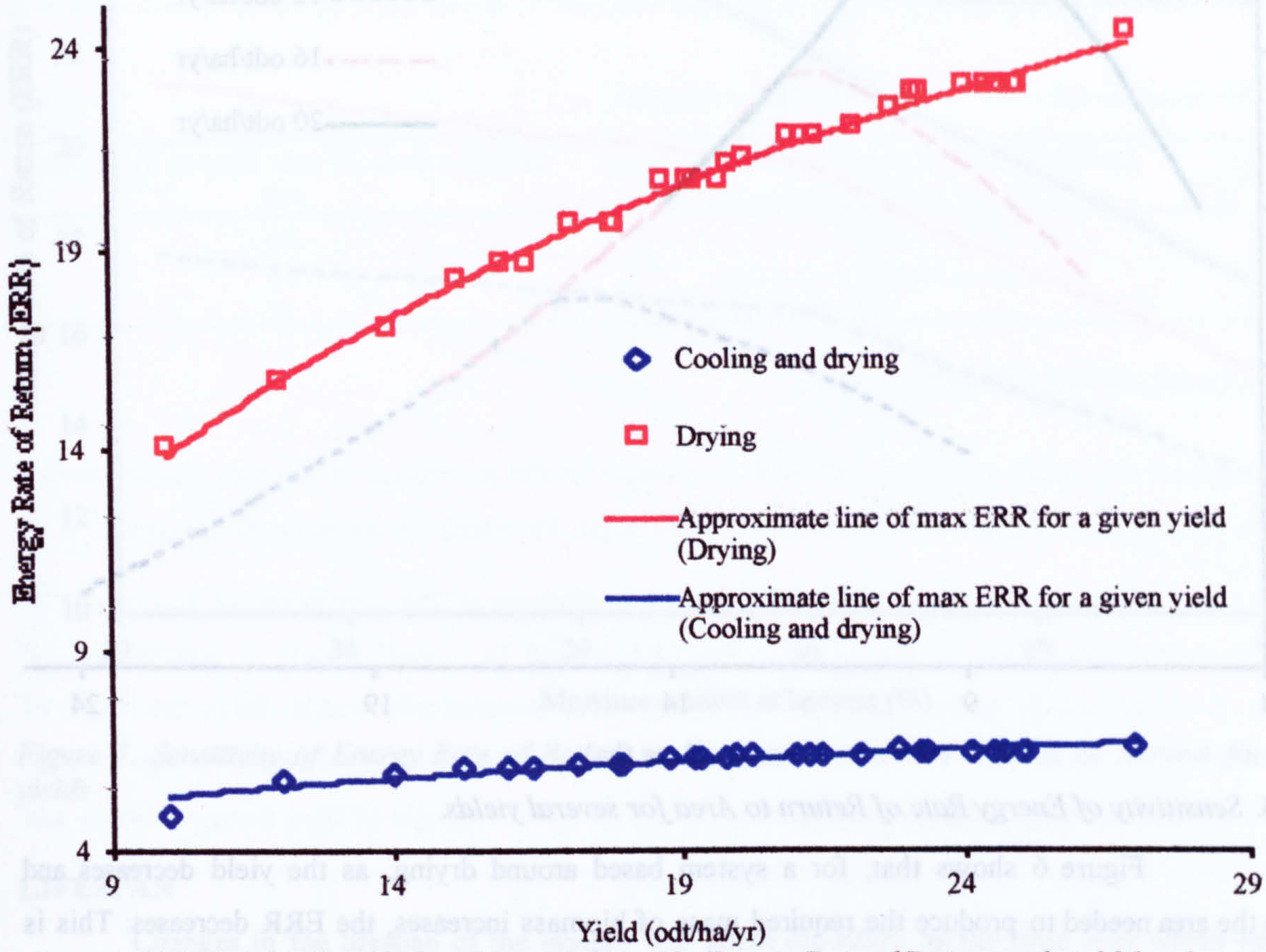

Figure 5. Relationship between maximum achievable Energy Rate of Return and yield for drying and cooling followed by drying.

SENSITIVITY ANALYSIS

Sensitivity analysis of the 30-kWe scenario was undertaken to examine the effect certain variables had on the ERR. The sensitivity analysis was done for three different yields for the optimum areas computed for these yields. These yields were 12, 16 and 20 odt.ha^{-1}yr^{-1}, chosen to give a representative span of the possible yields.

The sensitivity analysis has been done only for drying. The analysis for cooling followed by drying is so dependent upon the storage and preparation of the fuel that it makes the option far less desirable and the sensitivity analysis results inconclusive.

AREA

The area used to produce the crop is a critical variable. Sensitivity to area has been considered already, when considering the optimum size for a given yield. Figure 6 shows the sensitivity to area with drying for three different yields. From this it is possible to construct a line along which the maximum achievable ERR for a given area will lie, independent of yield. This maximum is obtainable because there is a limit to the quantity of biomass that a single machine can use.

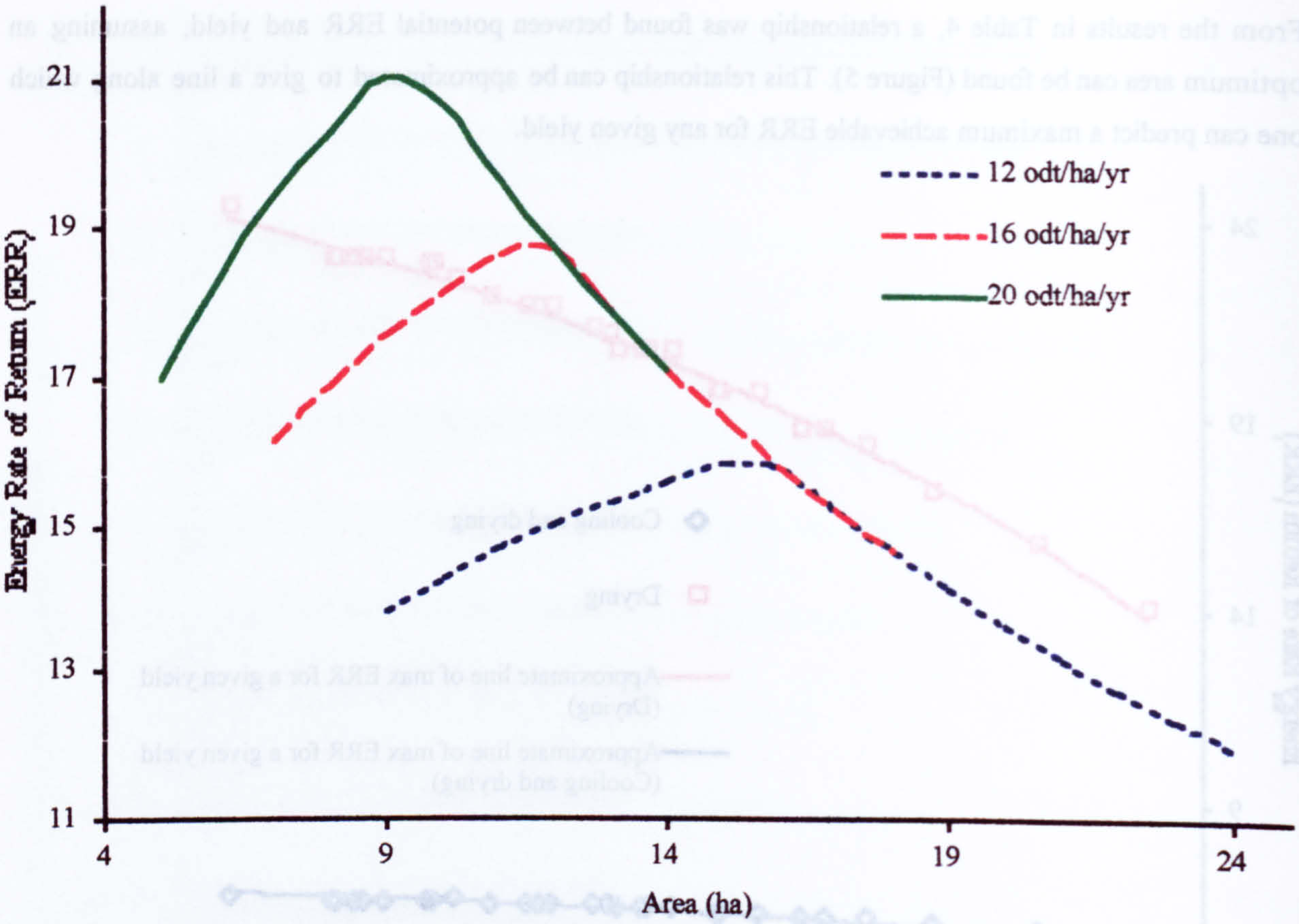

Figure 6. Sensitivity of Energy Rate of Return to Area for several yields.

Figure 6 shows that, for a system based around drying, as the yield decreases and therefore the area needed to produce the required mass of biomass increases, the ERR decreases. This is due to the extra time and therefore energy which must be invested in the agricultural operations to establish, maintain, harvest and decommission the cropping area.

MOISTURE CONTENT AT HARVEST

The moisture content at harvest will affect the storage process considerably. Choosing when to harvest the crop may be affected by the changes in ERR achieved by variation in moisture content at harvest. The results are shown in Figure 7.

Figure 7 underlines the sensitivity of ERR to the storage process. Increases in moisture content at harvest, and therefore energy expenditure in fuel preparation, have significant effects on the ERR. This effect is increased once the standard barn size must be increased to house the increase in size of the biomass. This increase in size is due to the assumption that dry woody biomass has the same volume as wet woody biomass in terms of dry weight. The wetter the wood, the larger the volume for the same quantity of dry biomass.

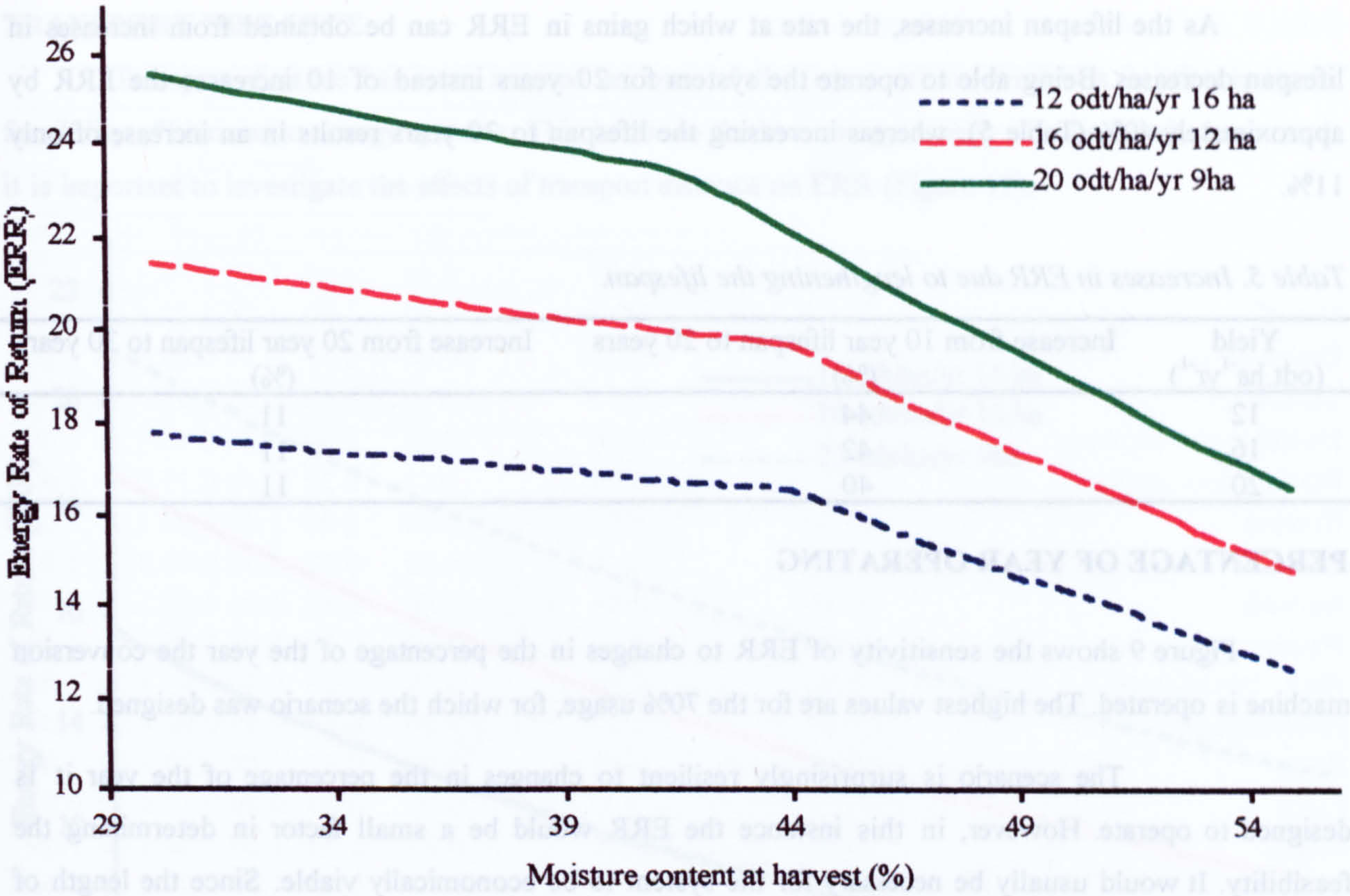

Figure 7. Sensitivity of Energy Rate of Return to changes in moisture content at harvest for several yields

LIFESPAN

Changes in the lifespan of the system will affect the ERR, as the time over which the energy cost of establishment etc. can be discounted changes (Figure 8). Prior to the fourth year there is an ERR of 0, i.e. there is not enough material harvested in the primary harvest, of one years' growth, to justify the running of the machine. This is due to the selection of a 3-year rotation period.

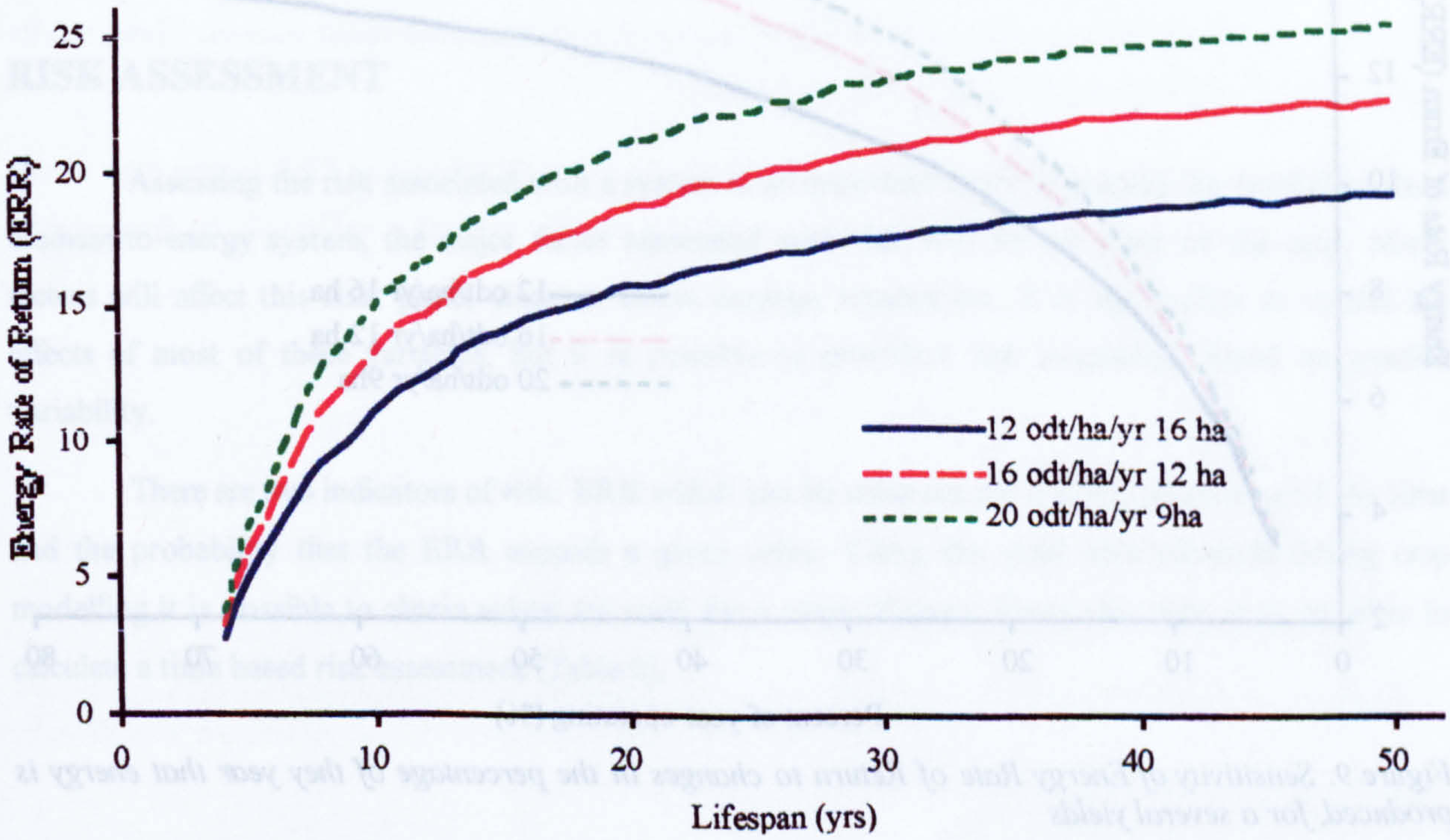

Figure 8. Sensitivity of Energy Rate of Return to changes in lifespan for several yields

As the lifespan increases, the rate at which gains in ERR can be obtained from increases in lifespan decreases. Being able to operate the system for 20 years instead of 10 increases the ERR by approximately 40% (Table 5), whereas increasing the lifespan to 30 years results in an increase of only 11%.

Table 5. Increases in ERR due to lengthening the lifespan.

Yield ($odt.ha^{-1}yr^{-1}$)	Increase from 10 year lifespan to 20 years (%)	Increase from 20 year lifespan to 30 years (%)
12	44	11
16	42	11
20	40	11

PERCENTAGE OF YEAR OPERATING

Figure 9 shows the sensitivity of ERR to changes in the percentage of the year the conversion machine is operated. The highest values are for the 70% usage, for which the scenario was designed.

The scenario is surprisingly resilient to changes in the percentage of the year it is designed to operate. However, in this instance the ERR would be a small factor in determining the feasibility. It would usually be necessary for the system to be economically viable. Since the length of time the machine is operating changes the quantity of electricity produced, and therefore any income, economics would play a large part in this decision. This is a good example of how energy analysis and economics must be considered complementarily.

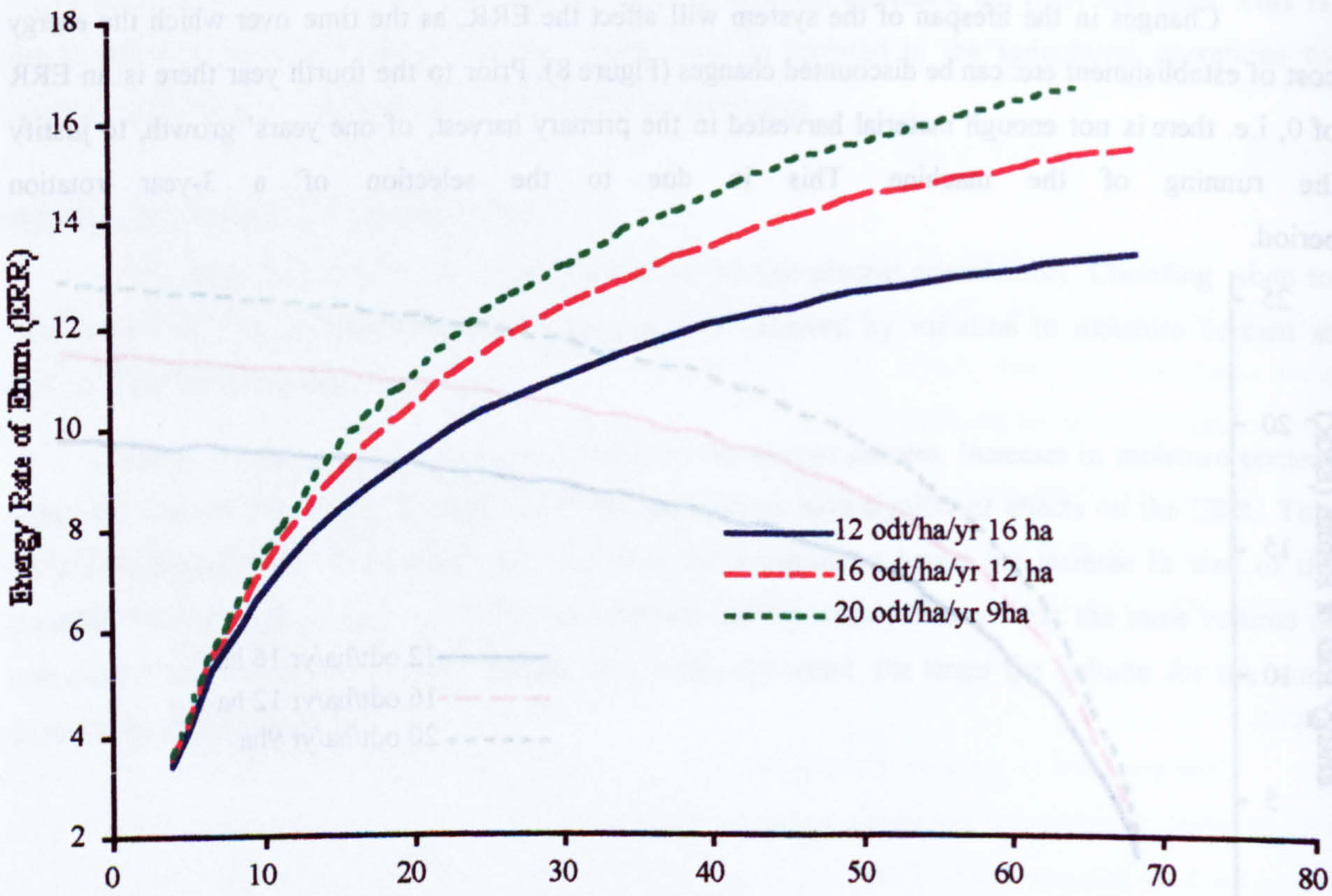

Figure 9. Sensitivity of Energy Rate of Return to changes in the percentage of they year that energy is produced, for a several yields

TRANSPORT DISTANCE

Transport distance has been mooted as one of the most critical variables in the energetic feasibility of biomass-to-energy systems. This is due to the low energy density of wood fuel. As a result it is important to investigate the effects of transport distance on ERR (Figure 10).

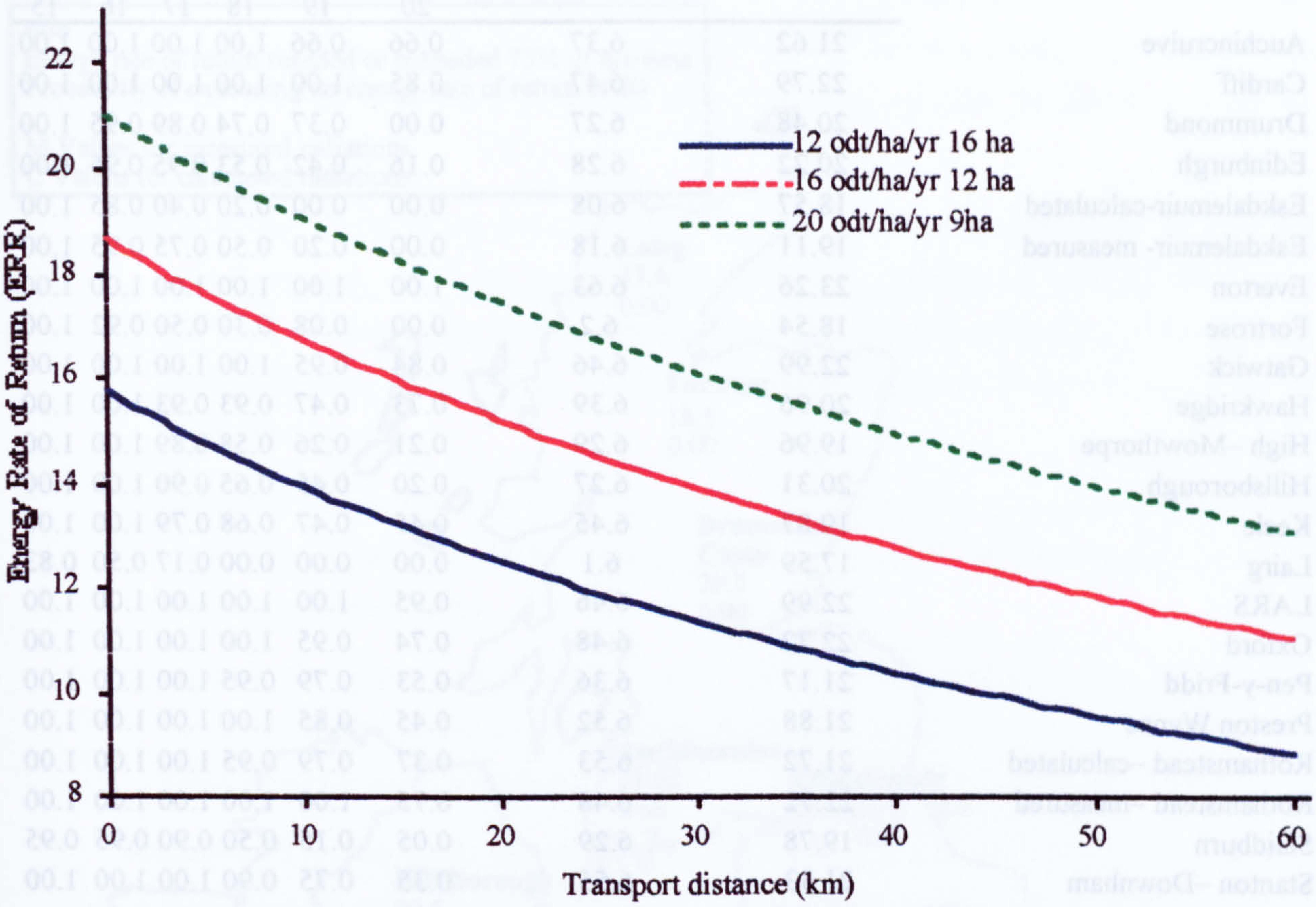

Figure 10. Sensitivity of Energy Rate of Return to changes in transport distance for several yields

As expected, the distance that the fuel must travel externally from the farm has a considerable effect on the ERR of the system, A distance of 60 km (37 miles) will almost half the ERR.

RISK ASSESSMENT

Assessing the risk associated with a system is an important factor in judging its feasibility. In a biomass-to-energy system, the major factor associated with risk will be the yield of the crop. Many factors will affect this risk: pests, diseases, storm damage, weather etc. It is impossible to model the effects of most of these variables, but it is possible to provide a risk assessment based on weather variability.

There are two indicators of risk: ERR which can be achieved for a given percentage of the time and the probability that the ERR exceeds a given value. Using the yield data obtained during crop modelling it is possible to obtain values for yield for a range of years. From this data, it is possible to calculate a time based risk assessment (Table 6).

Table 6. Risk assessment for individual sites.

Site	Drying	Cooling + drying	Drying					
	ERR for 75%	ERR for 75%	Probability of ERR exceeding shown value					
			20	19	18	17	16	15
Auchincruive	21.62	6.37	0.66	0.66	1.00	1.00	1.00	1.00
Cardiff	22.79	6.47	0.85	1.00	1.00	1.00	1.00	1.00
Drummond	20.48	6.27	0.00	0.37	0.74	0.89	0.95	1.00
Edinburgh	20.22	6.28	0.16	0.42	0.53	0.95	0.95	1.00
Eskdalemuir-calculated	18.57	6.08	0.00	0.00	0.20	0.40	0.85	1.00
Eskdalemuir- measured	19.11	6.18	0.00	0.20	0.50	0.75	0.95	1.00
Everton	23.26	6.63	1.00	1.00	1.00	1.00	1.00	1.00
Fortrose	18.54	6.2	0.00	0.08	0.30	0.50	0.92	1.00
Gatwick	22.99	6.46	0.84	0.95	1.00	1.00	1.00	1.00
Hawkridge	20.96	6.39	0.73	0.47	0.93	0.93	1.00	1.00
High -Mowthorpe	19.96	6.29	0.21	0.26	0.58	0.89	1.00	1.00
Hillsborough	20.31	6.27	0.20	0.45	0.65	0.90	1.00	1.00
Keele	19.87	6.45	0.45	0.47	0.68	0.79	1.00	1.00
Lairg	17.59	6.1	0.00	0.00	0.00	0.17	0.50	0.83
LARS	22.99	6.46	0.95	1.00	1.00	1.00	1.00	1.00
Oxford	22.72	6.48	0.74	0.95	1.00	1.00	1.00	1.00
Pen-y-Fridd	21.17	6.36	0.53	0.79	0.95	1.00	1.00	1.00
Preston Wynne	21.88	6.52	0.45	0.85	1.00	1.00	1.00	1.00
Rothamstead -calculated	21.72	6.53	0.37	0.79	0.95	1.00	1.00	1.00
Rothamstead -measured	22.72	6.48	0.75	1.00	1.00	1.00	1.00	1.00
Slaidburn	19.78	6.29	0.05	0.15	0.50	0.90	0.95	0.95
Stanton -Downham	21.33	6.55	0.35	0.75	0.90	1.00	1.00	1.00
Terrington	21.88	6.52	0.58	0.84	0.95	1.00	1.00	1.00
Warsop	20.96	6.39	0.30	0.60	0.90	1.00	1.00	1.00

Values for the percentage of time when ERR exceeds a given value are not given for cooling followed by drying because as yield increases ERR decreases rendering those result useless. These results are represented in geographical format in Figure 11.

The results of the risk assessment show that all the sites will achieve an ERR greater than 15 for nearly all the time based on potential production. The acceptability of such a value will be discussed in Chapter 9.

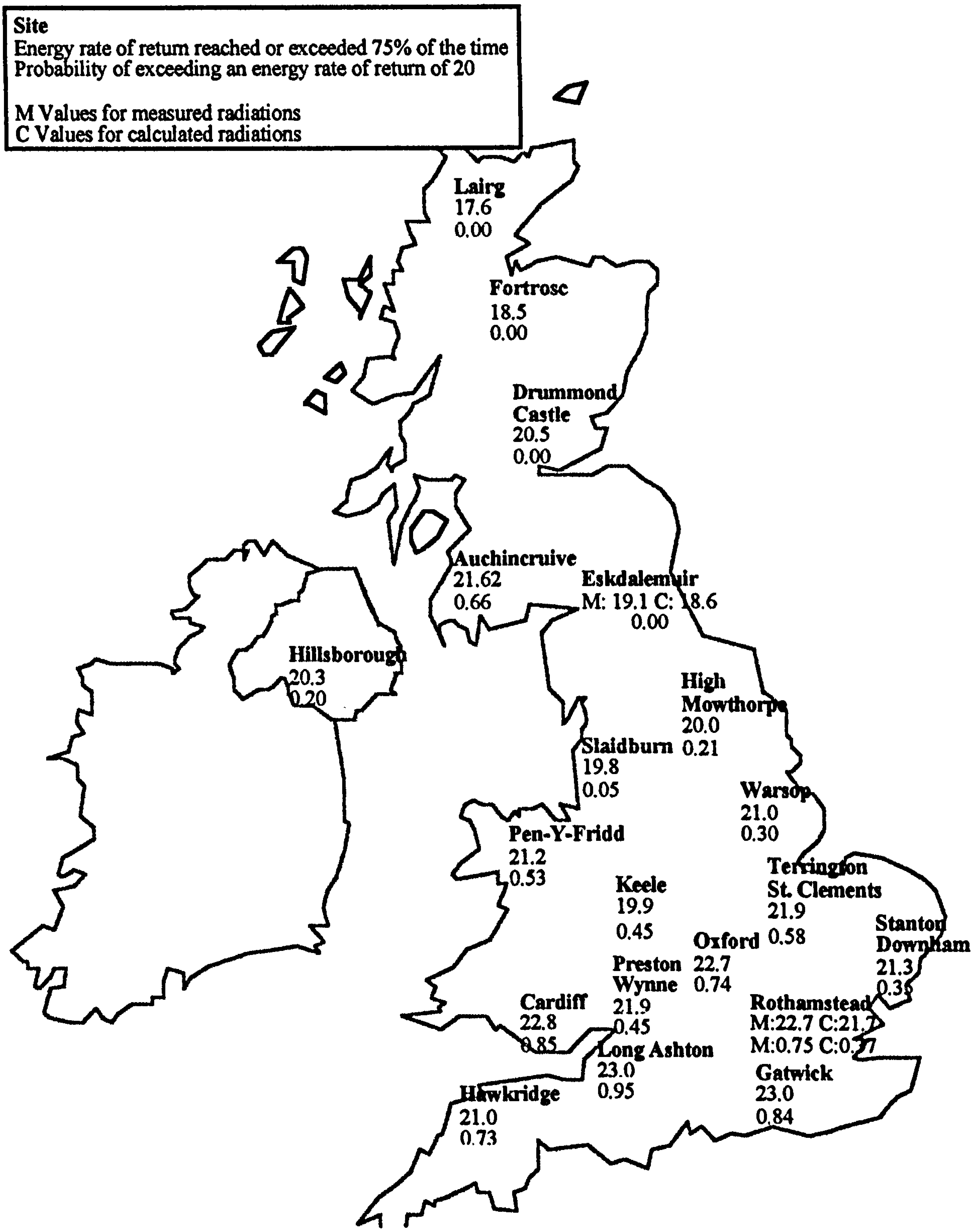

Figure 11. Map showing energy rates of return that are achievable 75% of the time and the probability of achieving an Energy Rate of Return of 20 for sites within the UK

CASE STUDY 1. TERRY ADAMS LTD

Terry Adams Ltd. has proposed a biomass-to-energy system to be sited on land reclaimed after a landfill site has been decommissioned. The proposed system is for a site in North Manchester. It will fulfil two needs for the company. It will provide a way of using land that cannot be used for food crops and must be managed in some way. It will also supplement the revenue from a landfill-gas-to-electricity production system that will be in place. A detailed list of the input variables for the analysis can be found in Appendix 2.

Establishment. Some of the area available (19 ha) has already been planted by hand. If the project were to go ahead, the rest of the area would be prepared using a plough and harrow and planted using a step planter, designed specifically for planting SRC. The planting density would be 10,000 per ha. A slow release herbicide would be used to keep weeds at bay in the first year.

Management. For the first three years herbicide would be applied every year, subsequently the management routine would be flexible but would probably involve the application of herbicide after each harvest.

Harvesting. Harvesting would be done with a forage harvester using a maize header. This should be capable of harvesting the whole harvestable area (19/3 = 6.33 ha) in one day. Damaged stools would be trimmed by hand.

Transport. The conversion and storage facilities would be sited within tractor and trailer distance of the crop so no extra transport would be necessary.

Storage. Chips would be stored in a barn with a floor designed to allow drying.

Conversion. Conversion would use a 30-kWe gasifier system based on the system discussed in Chapter 3 and identical to the system used in the 30-kWe scenario.

Decommissioning. There would be no decommissioning as after its useful lifespan the crop would be left to become part of the Red Rose community forest scheme.

RESULTS

The predicted yield by Terry Adams Ltd. for the site is 13 odt.ha^{-1}yr^{-1}. This yield needs only 14 ha to produce enough material to run the conversion machine. 19 ha provides a safety net in case of a low production year. Calculations (using BEAP) for this scenario have been done with yields of 13 odt.ha^{-1}yr^{-1}-19 ha, 13 odt.ha^{-1}yr^{-1}-14 ha and 20.2 odt.ha^{-1}yr^{-1}-9 ha. The 20.2 value is for potential production taken from the nearest of the sites in the crop modelling. The values obtained for ERR are shown in Table 7.

Table 7. Energy Rates of Return for a range of yields and areas.

Yield odt.ha^{-1}yr^{-1}	Area (ha)	ERR
13	19	14.92
13	14	17.54
10	19	14.92
20.2	9	22.09

The differences between the Terry Adams scenario and the standard 30-kWe scenario are not extreme. For this reason, a max ERR attainable for area graph (Figure 12) and a lifespan graph (Figure 13) are the only two sensitivity analyses included.

SENSITIVITY ANALYSIS

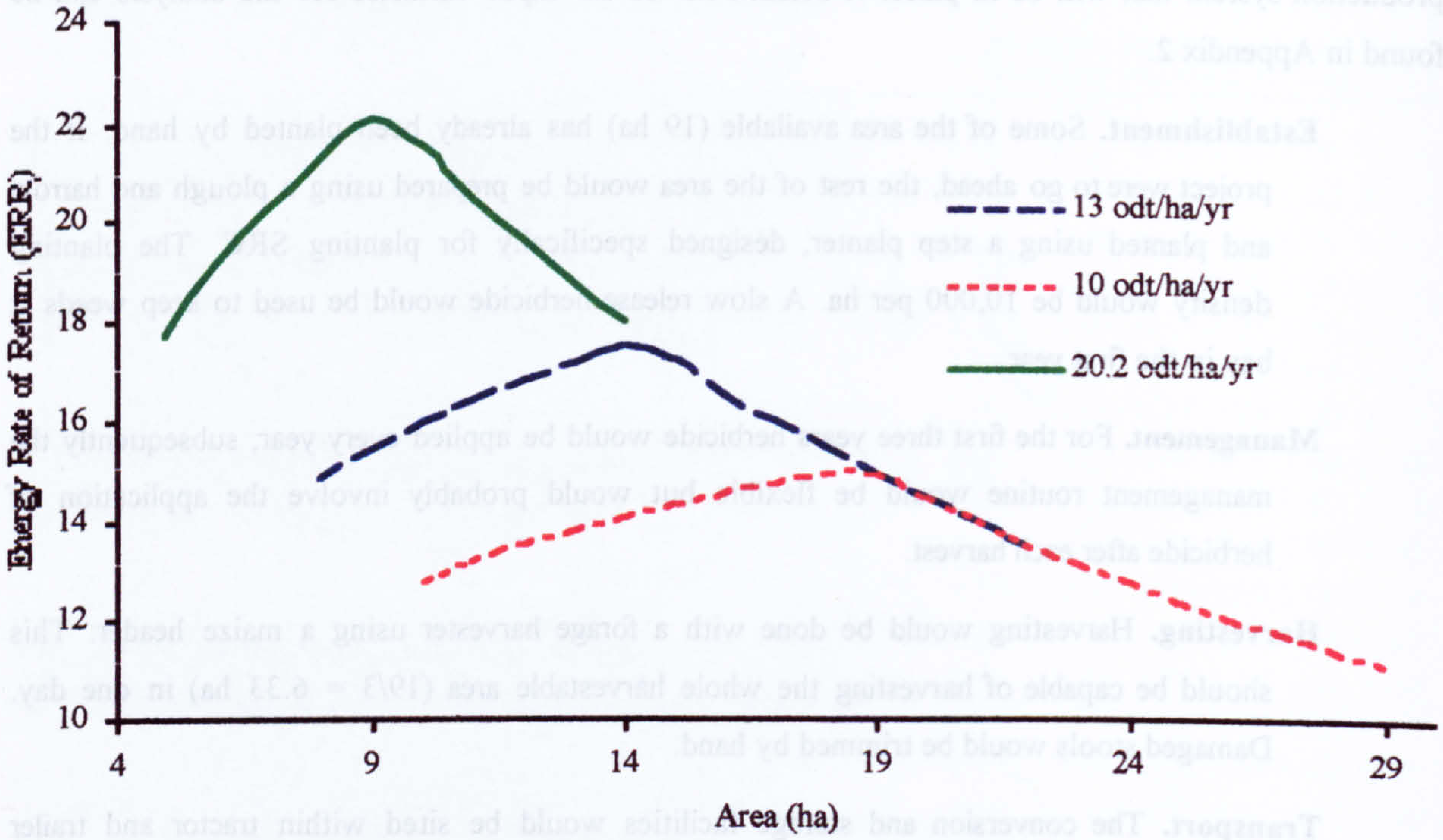

Figure 12. Sensitivity of Energy Rate of Return to changes in cultivated area for three different yields (Terry Adams scenario)

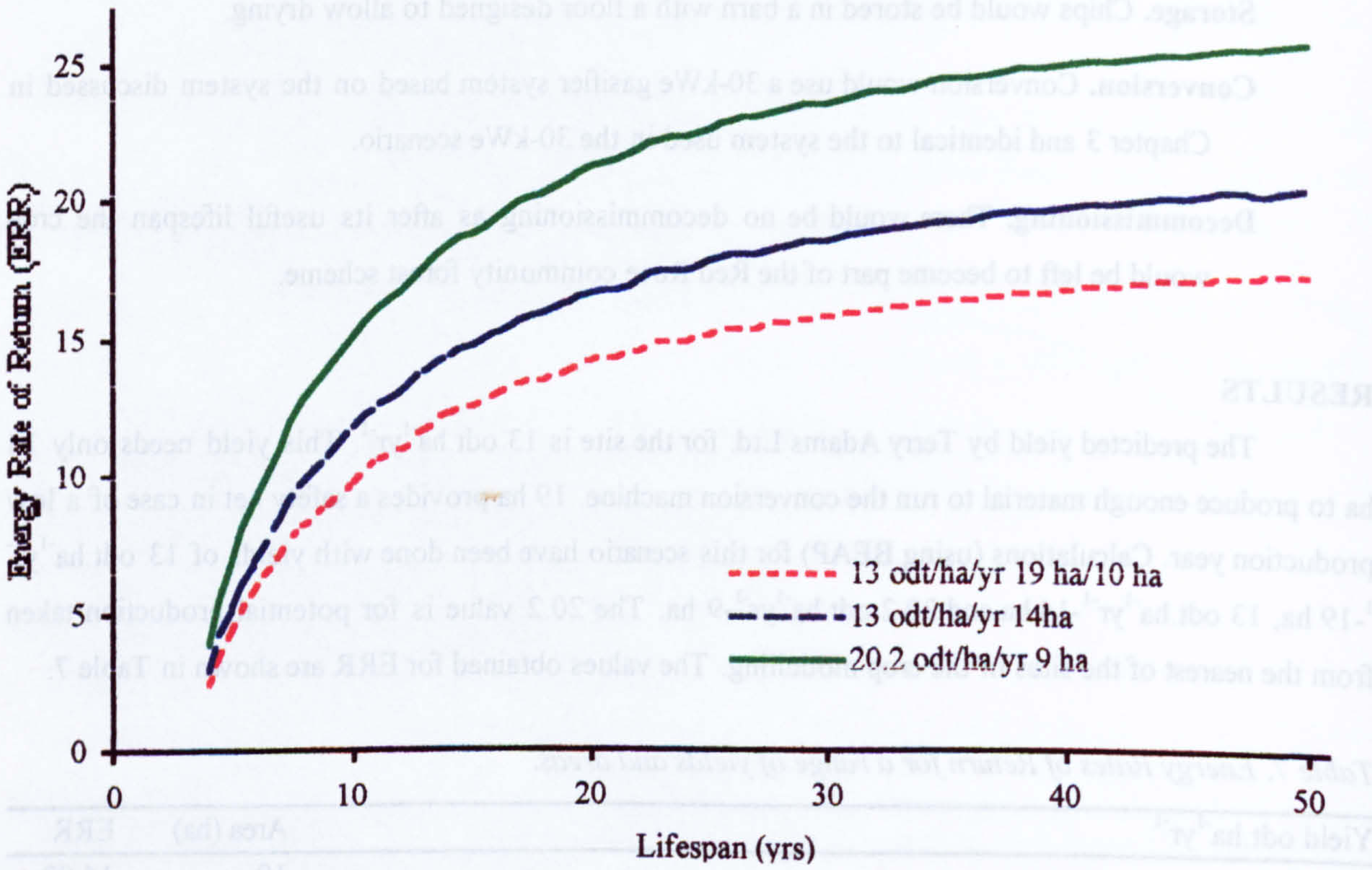

Figure 13. Sensitivity of Energy Rate of Return to changes in lifespan for three different yields (Terry Adams scenario)

Figure 12 shows the maximum achievable ERRs for a given area irrespective of yield. The results for this analysis are similar to those of the same analysis for the 30-kWe scenario. The slope of the curve describing the maximum attainable ERR is slightly different.

As with the analysis of area, the results from the analysis of sensitivity of ERR to lifespan (Figure 13) are close to those of the 30-kWe scenario.

CASE STUDY 2. TALBOTT-HILLS SYSTEM

A.F. Hills and Son are established willow growers, growing willows to provide cuttings in Worcestershire. To utilise excess willow production, they have installed a boiler system that heats and provides hot water for a large country house and swimming pool for a considerable period of the year. A detailed list of the input variables for the analysis can be found in Appendix 2.

Establishment. Hills use a modified cabbage planter to plant two rows at a time, at present needing two operators. This method can plant about 10,000 cuttings per day. If it was available a more efficient step planter would be used and therefore the calculations have been based around a Maskliner step planter.

Management. The crop is sprayed with a herbicide mixture in the first year. Subsequently it is sprayed every third year, if necessary. No other pesticides are used.

Harvesting. Harvesting is by hand and the stems are stored in bundles. This is because the main use of the willow is for cuttings. The bundles are left on the field margins. The willow not sold as cuttings is then hand-fed into a Turner T70 chipper producing a fine chip. The harvesting takes approximately two days per ha and chipping takes 1 day per ha. If it was available Hills would use a low ground-pressure vehicle that cuts and bundles stems. This is unlikely to happen in the near future, so hand harvesting has been retained in the analysis.

Transport. The chip is produced, stored and utilised on the same farm so transport is limited to tractor and trailer journeys.

Storage. The harvested bundles of stems are left on field margins to dry naturally. After chipping, the wood fuel is stored on the floor of a barn without any ventilation. The fuel is turned to avoid the build-up of enough heat to cause combustion. Masks are necessary because of mould. No extra drying is necessary.

Conversion. The conversion unit consists of a Talbott T5A boiler capable of producing 150 kW. The system is only used between October and May or April during which time it will run 24 hours a day for a week continuously before it must be de-ashed. The boilers have a hopper arrangement for fuel and this must be refilled every day.

Decommissioning. In the spring after final harvest when growth has started, the new shoots are sprayed with roundup. When the stools have died a scarifier and plough is used to revert the land to a useful state.

RESULTS

The analysis was done for yields of 12, 16, and 20 odt.ha^{-1}yr^{-1} to give an idea of the spread of values achievable. Calculations were also done for a potential production value of 22.8 odt.ha^{-1}yr^{-1}; this value was taken from the nearest site in the crop modelling work. The results are shown in Table 8. The area used at present is approximately 6 ha. It was assumed that all the heat used could be put to a use. This is probably a good assumption since the house is large and a swimming pool will consume considerable quantities of heat. The location of the system and house on the farm would also allow the heat to be used in the farm buildings.

Table 8. Results of BEAP model for Talbott-Hills scenario.

Yield odt.ha.$^{-1}$yr.$^{-1}$	Area (ha)	ERR
12	6	100.69
16	6	117.12
20	6	129.42
22.8	6	137.54

Sensitivity analysis was only done for yield, area and lifespan in this scenario, because it is an established system that relies on the continuation of a cuttings business. Therefore, there is little room for change.

The values for ERR are much higher in this scenario, compared to the other two scenarios, for two reasons. The efficiency of a boiler system to convert wood to heat is much higher than the efficiency of a gasifier system to convert wood to electricity. As well as this efficiency gain, much of the mechanised processes in the previous two cases have been replaced in this scenario with labour. This is because the primary reason for producing the biomass is not for heat and the labour-intensive processes are necessary for the business.

SENSITIVITY ANALYSIS

In this scenario as yield increases so does the ERR (Figure 14). This happens because there is an assumption that all the wood can be used as heat. This is a reasonable assumption up to a point, since from a 6 ha plot there is little chance that the Hills can use all the fuel produced within possible yield limits.

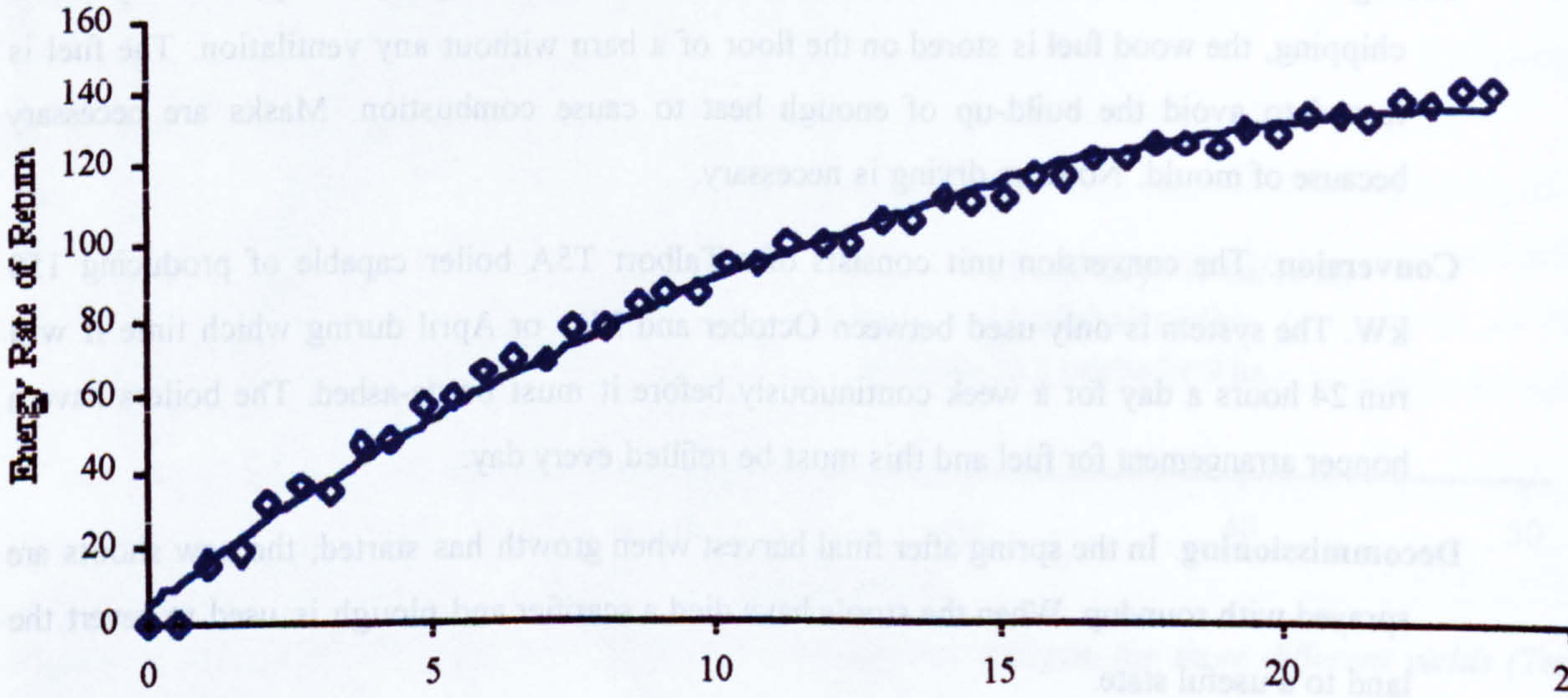

Figure 14. Energy Rate of Return vs. yield for Hills/Talbott scenario

As with area, the ERR increases as the quantity of fuel produced increases (Figure 15). In both instances (yield and area), it is noticeable that this gain decreases as the value rises. This is due to the higher energy cost of agricultural operations in these cases.

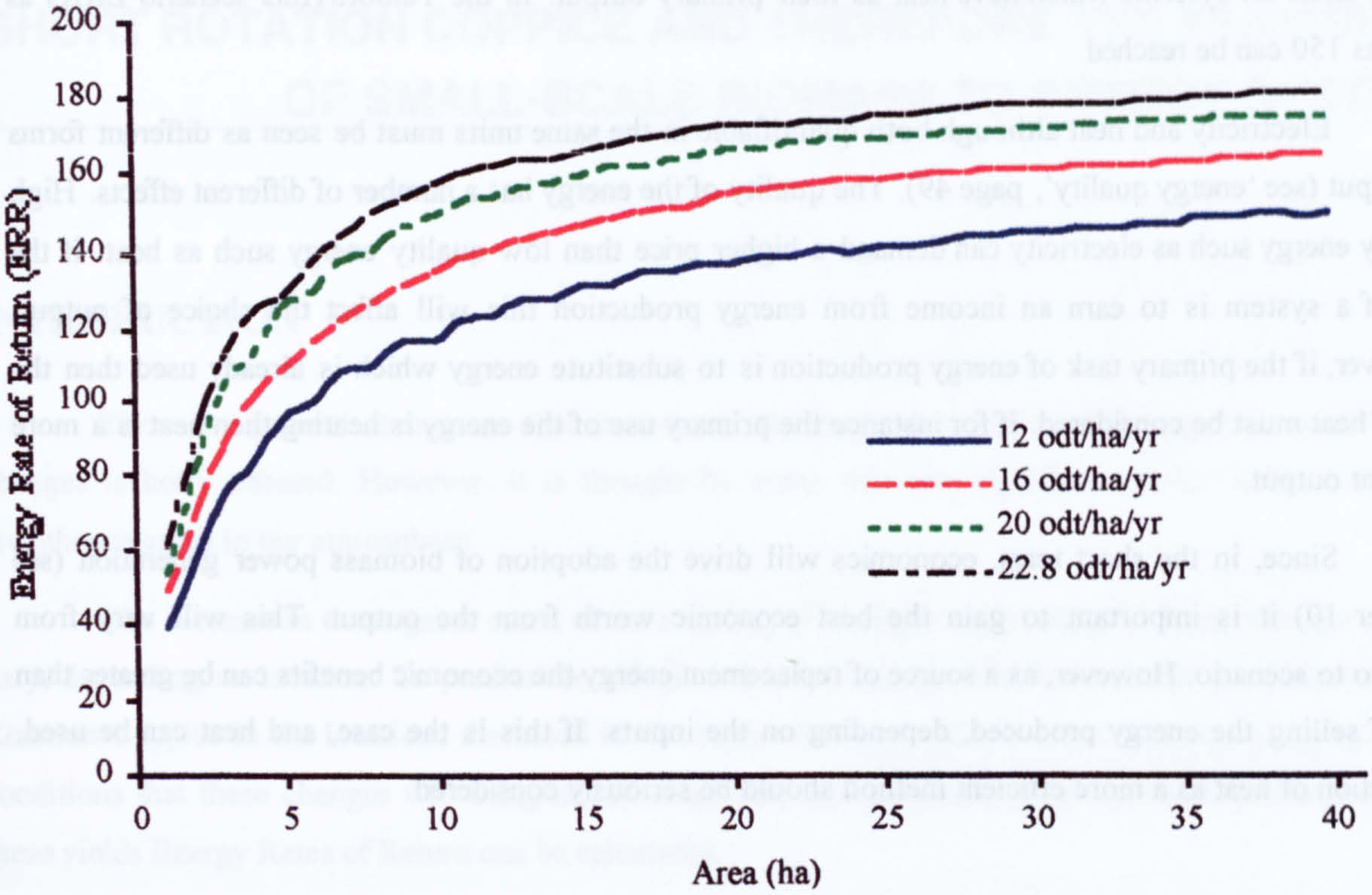

Figure 15. Sensitivity of Energy Rate of Return to changes in cultivated area for four different yields (Hills/Talbott scenario)

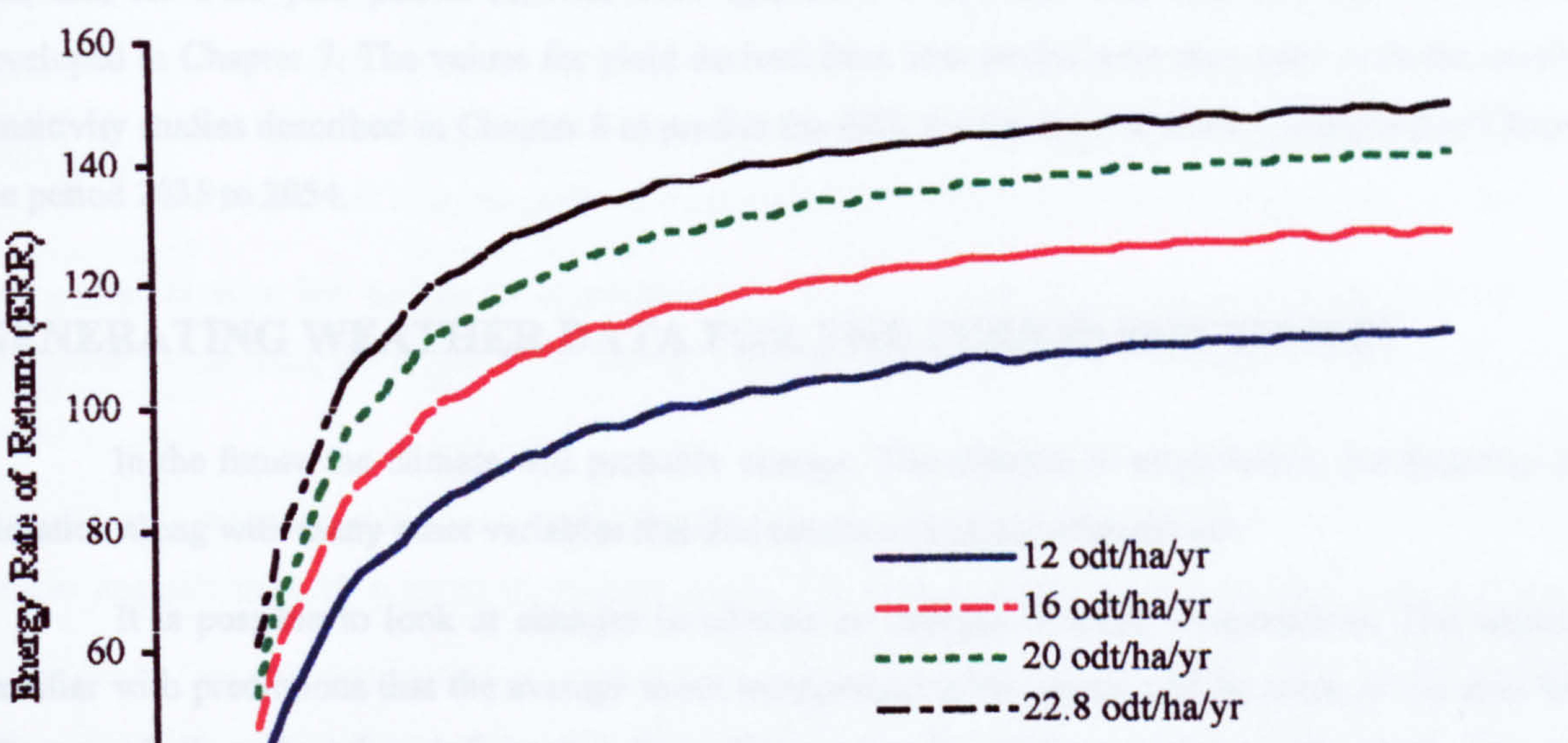

Figure 16. Sensitivity of Energy Rate of Return to changes in lifespan for four different yields (Hills/Talbott scenario)

The lifespan results for this scenario are similar to the lifespan results of the previous two for the same reasons, although the values for ERR are higher (Figure 16). As the lifespan increases so does the time against which the capital energy costs can be discounted.

HEAT VS. ELECTRICITY AND ITS EFFECT OF ERR

From the results of the analysis above it is obvious that it is possible to gain a significantly higher ERR for systems which have heat as their primary output. In the Talbott/Hills scenario ERRs as high as 150 can be reached.

Electricity and heat although both quantifiable in the same units must be seen as different forms of output (see 'energy quality', page 49). The quality of the energy has a number of different effects. High quality energy such as electricity can demand a higher price than low quality energy such as heat. If the aim of a system is to earn an income from energy production this will affect the choice of output. However, if the primary task of energy production is to substitute energy which is already used then the use of heat must be considered. If for instance the primary use of the energy is heating then heat is a more efficient output.

Since, in the short term, economics will drive the adoption of biomass power generation (see Chapter 10) it is important to gain the best economic worth from the output. This will vary from scenario to scenario. However, as a source of replacement energy the economic benefits can be greater than that of selling the energy produced, depending on the inputs. If this is the case, and heat can be used, production of heat as a more efficient method should be seriously considered.

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CHAPTER 9

THE EFFECT OF CHANGES IN THE CLIMATE ON YIELD OF SHORT ROTATION COPPICE AND THEREFORE THE FEASIBILITY OF SMALL-SCALE BIOMASS TO ENERGY SYSTEMS

INTRODUCTION

There is a general acceptance that the overall climate of the earth is changing. The cause of these changes is hotly debated. However, it is thought by some that one significant factor is the increase in greenhouse gases in our atmosphere.

The increase in these gases could cause a variety of changes in the climate. These changes will also vary, depending on location. To predict the effects that these changes will have on the production of Short Rotation Coppice in the locations discussed in this report it is necessary to have data regarding the weather conditions that these changes will bring about. From this data predicted yields can be calculated and from these yields Energy Rates of Return can be calculated.

To predict the changes a weather model (Semenov *et.al.*, 1997) has been used to generate weather data files for a 20 year period between 2035 and 2054. This data was then fed into the willow model developed in Chapter 7. The values for yield derived from that model were then used with the results of the sensitivity studies described in Chapter 8 to predict the ERR for the three scenarios described in Chapter 8 for the period 2035 to 2054.

GENERATING WEATHER DATA FOR THE PERIOD 2035 TO 2054

In the future the climate will probably change. The changes in temperature, precipitation and solar radiation along with many other variables that this entails will affect crop growth.

It is possible to look at changes in climate as changes in mean temperatures. The reader will be familiar with predictions that the average mean temperature of the world will increase in the next few years. These predictions, based on information from climate models, are very useful on the whole. However, they have their limitations when looking for the effect of climate variation on crop yields. Although changes in mean temperature have a significant effect, it has been shown that increases in variance in the climate have a large effect on the yield of crops. Significant changes in the extremes of heat or cold experienced by the crop will have significant effects as will the increase or decrease in periods of low or high rainfall. It is for this reason models such as that described in Semenov *et al.*, (1997) and Barrow *et al.*, (2000) have been developed to provide data for individual days within a future year. This information can then be used directly in existing calibrated yield models.

This work uses the model described in Barrow *et.al.*, (2000). This model is constructed from two elements: the HadCM2 Global Climate Model and the LARS-WG Stochastic Weather Generator.

Global Climate Models (GCMs) are models that describe predicted changes in the world's climate. These models produce data on a coarse grid structure (hundreds of kilometres). The information from these models is not suitable for direct use in making predictions at particular sites. The HadCM2 model is one of the most widely adopted GCMs since it has many improvements over previous versions. The version used in this work looks at the climate in the future based on increases in greenhouse gases.

The coarseness of the scale of the data from the GCM is overcome by combining the data with data from the LARS-WG weather generator. This is a series weather generator. A full explanation of the methods used in this generator can be found in M. Semenov *et.al.*, (1997). The LARS-WG weather generator uses 20 to 30 years worth of existing measured data to calibrate itself for the individual sites. The data that it produces have been compared with existing data and has shown a good correlation.

SELECTION OF SITES AND DATA

It was decided that the general elements for predicting yield for the future need not be applied to all the sites described in Chapters 7 and 8. As a result two sites were chosen for this work which would act as an indication of the effect in climate change. It was decided to use the same sites that were used in the calibration of the solar radiation equations in Chapter 7, Eskdalemuir and Rothamstead. These two sites represent different extremes of the climate which we are examining, as they are located at significantly different latitudes. There is also an abundance of measured data for these sites which helps in the calibration.

Data for these sites on maximum and minimum temperature, precipitation and solar radiation was calculated using the model described above. This data was then formatted for use in the yield model described in Chapter 7.

It was decided to stick to a 3 year rotation period as this has been accepted as the norm (see Chapter 7). The model was run for six 3 year rotations and one 2 year rotation to cover a 20 year lifespan of the plantation (Chapter 6).

RESULTS

The results for predicted yields for the period 2035 to 2054 are shown in Table 1. They are compared here to results for predicted yields based on the measured weather data available for these sites used in Chapter 7. It should be noted, once again, that these yields are potential yields and that the yield model does not take into account water or nitrogen stress.

Table 1. Predicted yields for Eskdalemuir and Rothamstead for the period 2035 to 2054 compared with predicted yields for the period for which there is available measured data.

Site	Period	Yield (odt/ha/yr)
Eskdalemuir (future predictions)	2035-2054	19.9
Eskdalemuir (past measured results)	1960-1993 (with breaks see Chapter 7 Table 1)	18.0
Rothamstead (future predictions)	2035-2054	24.5
Rothamstead (past measured results)	1971-1989	24.1

In Table 1 it is clear that the changes in yield produced by the changes in climate predicted by the model are not significant. The increase in yield predicted for Rothamstead is only 0.4 odt/ha/yr. The change in Eskdalemuir's yield is slightly more significant at almost 2 odt/ha/yr. This difference in yield variation between the sites is predicable as changes in the climate at the less clement end of the spectrum i.e. Eskdalemuir will have a more significant effect on the lower yields predicted there.

The predicted yield results shown in Table 1 can be translated into predicted Energy Rates of Return (ERRs) by comparing the results with the data for sensitivity calculated for the three scenarios in Chapter 8. The results of this comparison are shown in Table 2.

Table 2. Variations in predicted ERR based on yield fluctuations between results based on measured weather data and predictions for the period 2035 to 2054 for three different scenarios.

Site	Scenario	Yield Prediction Period	ERR
Eskdalemuir	General 30 kWe	1960-1993	19.62
Eskdalemuir	General 30 kWe	2035-2054	20.63
Eskdalemuir	Terry Adams Ltd	1960-1993	19.62
Eskdalemuir	Terry Adams Ltd	2035-2054	20.63
Eskdalemuir	Talbott-Hills	1960-1993	126.05
Eskdalemuir	Talbott-Hills	2035-2054	129.44
Rothamstead	General 30 kWe	1960-1993	22.99
Rothamstead	General 30 kWe	2035-2054	22.99
Rothamstead	Terry Adams Ltd	1960-1993	22.99
Rothamstead	Terry Adams Ltd	2035-2054	22.99
Rothamstead	Talbott-Hills	1960-1993	141.46
Rothamstead	Talbott-Hills	2035-2054	141.46

Table 2 shows that the variations produced by changes in predicted yield are of similar or less significance than the changes in yield. This is due to the fact that the entire yield cannot always be utilised in the production of electricity and heat since there is a limit, based on the area available and utilisation machinery.

The figures for Rothamstead show no variation due to the reason described above since the variation in yield at this end of the scale often results in discarding of material. The figures for Eskdalemuir show some variation since these values were at the lower end of the predicted yield scale. However the variations are between 2.7 and 5.1 % and do not represent a major change in the scale of the predicted ERR.

CONCLUSIONS

The data above show what may happen in the future to the ERRs predicted for the 3 scenarios described in Chapter 8. These changes are based purely on the yield predications developed from a model combining weather predictions and global climate changes.

The changes in predicted yield based on the predicted change in climate are not significant and therefore the changes in predicted ERR follow the same trend. It can be taken therefore that the feasibility of the system should not be affected by these changes in climate.

It should be noted that no attempt has been made to reflect the changes which will undoubtedly happen in the technology for biomass to energy conversion. Any increase in the efficiency of these processes would significantly effect the ERR. And since technology tends to progress, the ERRs for these systems should increase as time progresses. This will affect the feasibility of these systems in energy terms. However the affect on the financial practicality of the system is indeterminable as it is difficult if not impossible to make predictions on the fiscal structures which will surround energy production in the future, especially for this type of time frame.

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CHAPTER 10

THE EFFECT OF NON-TECHNICAL FACTORS ON THE FEASIBILITY OF PRODUCING ELECTRICITY AND HEAT FROM WILLOW BIOMASS ON A SMALL-SCALE

INTRODUCTION

In the last few years much of the discussion surrounding energy production from biomass has centred around what have become known as non-technical factors. These factors are diverse and include economic and social barriers which need to be overcome before biomass energy production can become an accepted and widely used technology.

The social factors included in this discussion are beyond the scope of this particular analysis. However the economic factors are very important to the perceived and actual feasibility of all biomass to energy systems and warrant discussion and investigation.

In this chapter the long-term and short-term factors associated with the economics of biomass energy production are discussed. A brief model of the small scale (30 kWe gasifier based) system described throughout this work is presented.

As mentioned in Chapter 5, economic analysis of a system can be seen as a partner to energetic analysis in determining the feasibility of a system. This work aims to place the findings of the energy analysis of systems described in this work within an economic context.

ECONOMIC FACTORS SURROUNDING RENEWABLE ENERGY AND PARTICULARLY BIOMASS

Energy, primarily in the form of electricity, is provided to the consumer via a competitive market place in most European countries. This means that for nearly all energy sources there is a competitive market in the supply of energy to the electrical distributors. This competitive market determines the price for which electricity is bought from the producer.

The market place is dominated, in most countries, by fossil fuel produced energy. The cost paid for this electricity by the distributor is determined largely by the price for which the producer can purchase fuel. The market place is considered by many to be distorted for this reason.

Fossil fuel energy supplies could be considered to be under priced for a number of reasons. Primarily discussion revolves around the need to account for the depletion of natural resources and the production of agents such as CO_2, CO and sulphurous gasses which are considered harmful to the environment. However there are other reasons that fossil fuels can be considered under priced. In Britain, for instance, state ownership of much of the primary industry (coal production, energy production and transport infrastructure) meant that the energy producing industries received an effective subsidy for a long period. The eventual sale of these industries, for what is considered by many to be a below cost value, has also subsidised the industry.

It must be pointed out that these factors do not effect the entire fossil fuel production system as the increase in new gas-fired electricity production facilities shows. These new facilities, which cannot be considered part of the old structure, are able to operate profitably in the competitive market place.

As already mentioned, with fossil-fuel energy the primary factors involved in producing an under priced product are that no cost is associated with the depletion of a finite resource or the production of pollution agents. Many studies have attempted, with varying degrees of success, to place an economic price on these factors.

The calculation of these costs, which are often referred to as hidden costs, varies in method. Estimates range from the low approx. 0.5 p/kWh to as high as 1,000 p/kWh (Goldthorp, 1996). These variations come from the wide variety of effects which can be attributed to pollution and resource depletion with effects such as global climate change attributing to factors at the high end of the scale.

LEVELLING THE PLAYING FIELD

The fact that so many variables distort the energy market, usually in favour of the producers using fossil fuels, creates a non-level playing field.

This imbalance not only favours the traditional energy production technologies but also hinders new technologies because of the high R&D costs and other costs associated with the production of clean or renewable energy. To enable these new and arguably environmentally and socially beneficial technologies to develop, some effort needs to be made to level the playing field.

Many models exist to bring about this change. Subsidisation of non-fossil fuels and carbon taxation are two of the most discussed solutions with the former most commonly used. Many would argue that the governmental interference in the market place required by such measures would have an adverse outcome and also that this is not a form of action appropriate to a modern monetarist economy. This argument does not however take into account that governments are adept at manipulating what is perhaps the most important market place in a modern industrialised economy. The use of taxation has long been used to manipulate fuel prices for the long-term and short-term needs of governments. The continually increasing taxation on petrol is an example of this manipulation.

SUBSIDISATION AND NFFO

At present the UK government has been using a subsidisation tool called the Non-Fossil Fuel Obligation (NFFO) to help non-fossil fuel based energy production gain a footing in the energy market place. The NFFO was initially designed to help subsidise the running and eventual decommissioning costs of nuclear-based power. In the past few years however, this obligation has been used with great effect to help develop renewable energy resources.

An example of the success of NFFO is wind power. Wind was one of the first renewables to benefit substantially from the NFFO tranches.

In the initial phase the price which the suppliers were obliged to pay for the electricity (set by the NFFO order) was as high as 11 p/kWh for wind power. This is a very high price compared with the pool prices of 2 -3 p/kWh. These prices made wind a viable economic proposition (from the producers perspective) and encouraged many people to developing wind farms. With this development, technology and other factors affecting profitability increased to the point where wind is now a technology that can compete with traditional power sources.

The effect that such subsidies can have will be shown in the economic analysis later in this chapter. Values in the last tranche of 2.34 - 4.60 p/kWh (ETSU, 1998) for a variety of technologies, shows the effect the obligation can have on profitability when the pool price for energy is approximately 2 p/kWh. These obligations are for a period of 15 years. This form of subsidisation can lead to projects which would otherwise seem either non-economic or high risk proceeding.

However, there are a number of problems with the NFFO funding scheme. When an NFFO order is set out it defines the different fields of technology which it is going to fund (wind, biomass etc.). It is within these bands that submissions are requested. Once a number of criteria have been complied with the selection is made on a lowest cost basis (ETSU, 1999[1]). This can hamper the development of small-scale and less developed technologies. For instance, within the biomass band small-scale gasification which is in need of further development will be competing against more economic steam power generators of a larger scale.

The aim of NFFO in the long run is to also aid a convergence of the price of renewable energy with non-renewable sources (ETSU, 1998[1]). This is done through selecting the cheapest bids as mentioned above. Economically unattractive but environmentally sound technologies will be left behind by this approach. This gap is likely to be larger using the NFFO method than the gap, if any, that would arise from taxation of supply on the basis of production (see the section on carbon tax).

However, even with these limitations, biomass as a whole has profited from the NFFO order. As of 31 March 1999 there were 6 active biomass projects with a total capacity of 64.284 MW in the UK excluding NI and Scotland (ETSU, 1999[2]). There are also another 26 projects which have not gone live with a further capacity of 191.676 MW. This proves that there are people who believe it is possible to generate electricity economically from biomass with the implementation of NFFO.

Although there is a demonstrable market and economic benefit from biomass as shown above, this does not necessarily apply to gasification on either a small or large scale. Only one set of NFFO awards has been made for gasification of biomass projects, NFFO 3. This has contracted for 3 projects at a capacity of 19.056 MW. However as of 31 March 1999 none of these projects were live (ETSU, 1999[2]). Although non-economic reasons could be the cause, it is also possible that the obligation they were given would not make the projects economically viable in the current market place.

This form of subsidy is a very useful tool in the development of renewable energy resources. It will be shown later that such subsidisation would probably be necessary for if it is to become a player in the UK energy market.

CARBON TAXATION

The production of CO_2 from traditional fuel reserves is a significant factor in the increase in CO_2 levels. This has been seen as a major environmental problem for the future. One approach to curbing this rise has been to look at the introduction of carbon taxation on fossil-fuel based energy production. Biomass has a place to play in the reduction of CO_2 (Hall, 1990; Swisher, 1994; Lunnan, 1997) and as a result would benefit from such a tax. It is however debatable whether carbon taxation will benefit biomass to the extent that it will become competitive with fossil fuels (Lunnan, 1997).

Carbon taxation would have the effect of levelling the playing field as it would increase the cost of producing energy from technologies using fossil fuel resources. This form of modification to the market place would have a more drastic impact than subsidisation methods such as NFFO.

In the long term, carbon taxation could provide a much better solution than government subsidisation. It would apply to all producers and the narrow band of producers who manage to obtain subsidy under the NFFO tranches would not be the only beneficiaries of the levelled field. A solid entrenchment of these forms of taxes would also provide a more stable and competitive long term market and push larger investors into technologies which at present are the preserve of the dedicated enthusiast.

The disadvantages of such a system are the increased taxation load to the industry and the inevitable increase in product cost to the consumer. However, in an environment which is almost definitely being adversely affected by the continued use of fossil fuels these may be prices worth paying to ensure long term benefits.

POTENTIAL FOR RENEWABLES ASSUMING THAT NON-TECHNICAL BARRIERS ARE OVERCOME

Assuming that the non-technical barriers for biomass are overcome - is there a potential for biomass within the energy producing structure of the present electricity based system?

The answer is very important to the long-term development of biomass as a renewable resource. Factors such as the potential for production (discussed in Chapter 1) and the stability of the grid, pose questions here. Also, is it theoretically possible to use subsidisation or carbon taxes in such a way that biomass does become an economically competitive solution?

POTENTIAL FOR PRODUCTION

There is an obvious potential for production of electricity from biomass within the UK. This has been demonstrated by the calculations in Chapter 1. This potential is also borne out by the experience of other countries where biomass has taken on a more substantial role in energy production than in the UK. In Sweden estimates show that in 1997 biomass made up between 13.1% and 18% of the country's total energy production although most of this is forest waste (Johansson and Lundqvist, 1999; Roos et al., (1999)).

Figures like these show that with the correct economic incentives whether from subsidy or from a method of production that is economically competitive with existing sources, biomass can be a competitive energy producer. This potential justifies the examination of biomass by energetic and economic methods.

There have been many studies concerning biomass economics outside the UK. Usually these are based on large scale production of electricity, often from biomass waste products. The results vary, however there are studies which have concluded that it is possible to competitively generate electricity from biomass (Gopalakrishnan *et al.*, 1993; Sims, 1994).

GRANTS AND OTHER AVAILABLE SCHEMES FOR BIOMASS ENERGY

There are a number of grants that in some way benefit the UK biomass energy producer. These schemes are based on the use of the land providing the biomass. Set-aside and the woodland planting grant are probably the two most common examples.

These schemes have become of great interest to potential biomass energy producers and to the proponents of this technology. The initial calculations on potential for biomass production in this work were made on the assumption of set-aside. However it is the author's opinion that basing economic assessments of biomass to energy systems on this is not a good way to proceed.

The set-aside scheme which provides grant aid for farmers, who set aside a percentage of their land for non-food production, is based on the European Union's (EU's) need to reduce farm output. This scheme has been prone to fluctuations in the percentage of farm area to which it applies. In the long term, 20 years is the term of the biomass scenario in question here, the set-aside scheme could not be relied upon to continue in part or in whole for this period.

Another scheme which is often used in economic analysis of biomass energy systems is the woodland planting grant. This is a grant given for areas of land which are turned into woodland. It appears that coppice willow would fall into this category and therefore be covered by this payment. However, in the long term it is the author's opinion that coppice willow may be removed from this net. SRC does not constitute a long term woodland but a longer term than normal crop with cyclical variations in area. Even if SRC were to remain within the woodland planting grant the concerns mentioned above regarding the long term factors affecting set-aside must also be voiced about the woodland planting grant.

Because of these concerns neither of these two schemes have been included in the economic assessment of the project below.

ECONOMIC ASSESSMENT OF THE 30-KWE SCENARIO

To assess the current economics of the small-scale scenario described throughout this work a simple economic model of the 30 kWe scenario is a useful tool in determining the overall feasibility of such small scale biomass to energy systems. Such a model has been developed and its development and results are outlined below.

Such modelling of biomass systems is not new. Models have been developed before which attempt to address the economics of biomass energy productions systems (Goldthorp, 1996; Sourie *et al.*, 1996). The model below is not intended to be as thorough an analysis as either of these two examples but is intended to give an accurate representation of costs and benefits for the proposed scenarios.

MODELLING METHOD

As with all economic models the primary function here is to summate the cost of inputs and the outputs of the system in a monetary form. As with energetic analysis much of the reliability of such a model depends on the quality of the data available for inputs.

INPUTS

The small-scale scenario envisaged and described in Chapter 3 is seen as an additional agricultural activity and not an exclusive use of a farm's arable area. Therefore the inputs associated with machinery costs relating to the agricultural activities cannot be solely attributed to the production of the energy crop. It is also probable that some of the agricultural operations will be performed by contractors as specialised machinery such as planters and forage harvesters are rarely owned and operated by individual farmers. Because of these assumptions figures for contract or per job costs are used in the model below.

The method of attributing costs mentioned above has not always been used in previous economic models of similar systems. It is common to attribute the purchase of agricultural machinery to the production of biomass crops. This method is seen as irrelevant to the small scale scenario investigated here as the size of cropping area would not justify the purchase of machinery solely for the use of this crop.

Figures for contract work are readily available The *farm pocket handbook* (Nix, 1996) is used widely across the agricultural industry and provides standard prices for operations. In the model described below figures from this have been used wherever possible. However figures for certain operations are not available from Nix and in these instances figures from available literature are used. Table 1 shows the figures used and their sources.

Table 1. Costs of agricultural and mechanical operations used as inputs into economic model

Function	Unit	Cost Per Unit £	Source
Tractor and sprayer	ha	32.35	Nix 96
Tractor and plough	ha	34.5	Nix 96
Tractor and harrow	ha	23	Nix 96
Tractor and rotavator	ha	53	Nix 96
Step planter	ha	540	Nix 96
Harvesting	ha	100 to 1600Ψ	Nix 96, Carter 1991, Mitchell et al. 1999.
Conversion	unit	30,000 to 60000	Rod Parfit 1997
Conversion building	m2	52	Nix 96
Drying	tonne	4.8372*	Nellist et al. 1993
Drying building	tonne	300	Nix 96

ΨThe lower figure here is based on conventional forage harvesting from Nix (1996), the higher figure on an estimate by Murray Carter. The wide variation in this mean that results based on both figures are given later
*This is using 0.02 £ per kWh and figures for drying

OUTPUTS

Accounting for outputs is a simpler operation. It is assumed that the heat produced by the system is not an economic resource and so it is not included in the calculations. Excess fuel (wood chip) is also considered not to be an economic resource and is not included in the calculations either. Without these two the only source of income is the sale of electricity. The price at which this electricity can be sold is obviously of great importance and greatly affects the economics. Consequently data showing the effect of changes in electricity price is shown.

DISCOUNTING INCOME

The model described in this work attempts to describe the system over a period of 20 years. This is a long period economically and the costs and outputs may vary widely across this period. To account for this a method called discounting can be used. This method accounts for time assuming that a unit of currency is worth more now than it will be in the future due to inflation. Using this method future income is discounted to its present monetary worth using a mathematical formula.

$$Present\_Value = Value_n \times (1+i)^n \tag{1}$$

where n = year and i = interest rate

This equation can be used to calculate the income for the years that the model runs and create a projected profit or loss in terms of current monetary values.

MODEL CREATION

The model itself was built using Microsoft Excel as a single spread sheet. The input data (as described in Table 1) were fed in as well as values for a wide range of constants and control variables (described in Table 2).

Table 2. Control Variables used in economic model.

Variable	Value	Unit
Discount rate	12	%
Interest rate	10	%
Yield	20	odt/ha/yr
Ha per rotation	5	ha
Rotation period	3	yrs
Size of conversion building	15	m2
Dry moisture content	15	%
Wet moisture content	46	%
Wet weight	31.5*	t
Dry weight	23.5*	t
Total area	15	ha
Price per kWh	variable	£

* these values are calculated on the basis of the moisture contents wet and dry.

Using the model it was possible to modify some of the control variables to see how this affected the projected profit and loss.

RESULTS OF ECONOMIC MODEL

The variables detailed in Tables 1 and 2 were fed into the spreadsheet model. The results of this model are described below in terms of their sensitivity to certain variables. To deal with variations in the input variable of the conversion machinery and harvesting costs two different sets of results were produced. The first set is a best case situation with the lowest values in each. The second is a worst case scenario with the highest of these two variables.

The profits for each year are discounted to the present value and any capital expenditure incurred in the startup of the project is paid off on a loan based on a 20 year payback and a 10% interest rate. Both these figures are conservative to say the least.

EFFECT ON OVERALL PROFIT OF THE PRICE OF ELECTRICITY

Table 3. The effect of changes in the price paid for electricity on the overall profit of the system.

Price paid per kWh (£)	Profit (£)	
	Best Case	Worst Case
.01	-30,484	-92,728
.02	-17,893	-80.137
.03	-5,302	-67,545
.04	7,289	-54,954
.05	19,880	-42,363
.06	32,472	-29,771
.07	45,063	-17,180
.08	57,654	-4,588
.09	70,264	8,002
.10	82,837	20,593
.11	95,428	33,185
.12	108,020	45,776

From Table 3 it can be seen that the profitability of the proposed small scale scenario is not good when electricity is sold for a price similar to the pool price (.01 to .03 £/kWh). The best and worst case scenarios make a considerable loss at these prices.

It is not until the price paid is significantly above the pool price, .04 £/kWh in the best case scenario and .09 £/kWh in the worst case scenario, that any profit at all is made from the system.

OTHER FACTORS CONCERNING THE ECONOMIC VIABILITY OF BIOMASS FUELS

There are a number of other factors which can affect the economics of a biomass fuel system especially at the scale considered here.

PEAK LOAD PROVISION.

It is possible to earn a significantly higher price for electricity if it is sold upon demand for peak load provision. There are fluctuations in energy demand and these have to be provided for by the electricity suppliers. A higher price can be commanded if machinery is supplied which is capable of being started remotely within 20 minutes. At present this is not the case with the gasifier system described in this work and, in the author's opinion, not with any of the other small scale biomass facilities either. But in the future, with more development, such a system could provide an increased revenue stream.

STORAGE

Traditionally fossil fuel reserves have been stockpiled by governments or producers to meet emergency demands. These stockpiles can contribute to the cost of electricity production (Lunnan, 1997). There is some research which shows that there is an economic benefit to the elimination of these resources which could be as much as £0.175 per MWh (Carlson and Karlsson, 1996).

COMPETITION WITH TRADITIONAL CROPS

It must be remembered that biomass energy crops are to be grown as an agricultural product on farms in most scenarios. In this case the farmers must be persuaded that not only is there a profit to be made but that this profit is the best that they can get from the land. The use of small-scale generators helps here as the farmer benefits from the increased profit of selling a high value product like electricity over a low value product like wood chip.

However the profitability at this level is at best suspect. Biomass compares unfavourably next to other crops. It is possible to earn more money from the growth of wheat than from biomass (Lunnan, 1997).

At the moment the profitability of biomass relegates biomass to the role of filling land not used for food production (set-aside, marginal land). Biomass can grow well on some marginal land but this does mean that in the near future it is unlikely to rival food crops as a profitable venture. It is therefore unlikely to make a large impact on energy production in the short term.

CONCLUSIONS

The figures of .04 and .09 £/kWh are not as fanciful as they may seem. In the last NFFO tranche the top price paid to producers was .046 £/kWh and in the past prices of up to .11 £/kWh have been given to producers under NFFO (although it should be noted that the rules have since changed).

The costs associated with the worst case situation above are high in the author's opinion. The cost of harvesting is reducing with the development of new and faster machinery for the process. Another salient factor is that the harvesting schedule of SRC differs from most other crops, as it happens during the winter. In the author's experience this has lowered the cost of harvesting as the contractors who carry out this work are prepared to work for lower rates out of season.

The cost of generating machinery will also decrease. If gasifier engine systems of the type envisaged here were to go into large-scale production, the costs could be significantly decreased with economies of scale. It is also possible to contract some of the less specialised manufacturing jobs to less skilled labour or have them carried out on site by existing workers.

When combined, these factors make the best case scenario a better long-term indicator in the author's opinion. However even looking at this better situation does not make the scenario profitable at current electricity prices. Prices would have to rise substantially or be subsidised significantly for this system to be economic in the current economic climate.

These rises in electricity cost are not impossible (note the variations in proposed carbon use costs) however this does not seem likely in the short term. In fact in the medium term (i.e. next 20 years) it is likely that fossil fuel prices will decrease (Lunnan, 1997; Radetzki, 1997).

Subsidisation from NFFO or other sources to the extent that this form of system would be significantly profitable is also unlikely as there is a trend towards smaller increases over pool price by the NFFO body. Economic viability in the current market place could only come from decreases in costs.

There are other options that should be evaluated. If the electricity can be used to replace electricity bought from the grid and possibly heat, the economics of this system could change. Current consumer prices for electricity are approximately 4 to 5 p/kWh and at these values one could not only save money on existing electricity but also cover the costs of the generating system.

However, in general the economic outlook is not good. It is a demonstration of the unevenness of the playing field that an energetically more efficient electricity production system such as small scale biomass cannot compete economically with less efficient competitors such as coal, gas and nuclear. Even when these barriers are overcome many other non-technical barriers remain (Roos *et al.*, 1999).

Although the outlook is bleak, biomass may well have a role to play at the small scale in the future. Research has show (Moxnes, 1991) how small stimuli in the form of subsidisation of research costs or electricity price can determine the future competitive market place. Use of such stimuli should be considered by governments to facilitate a more efficient and environmentally sound energy production future.

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CHAPTER 11

DISCUSSION AND CONCLUSIONS OF PRACTICAL AND THEORETICAL FEASIBILITY STUDIES OF SMALL-SCALE ELECTRICITY PRODUCTION FROM SRC-WILLOW BIOMASS

INTRODUCTION

The purpose of the work in this thesis was to investigate the practical and theoretical feasibility of producing electricity from Short Rotation Coppice (SRC)-willow biomass. The work was divided into three sections:

1. Practical investigation of a 30-kWe downdraft gasifier system.
2. Energy analysis/risk assessment of small-scale biomass-to-energy systems.
3. Assessment of non-technical factors affecting biomass and in particular the economics of a 30-kWe system.

Practical studies have centred on determining the efficiency of a 30-kWe downdraft gasifier and generator system in use at IACR-Long Ashton Research Station (LARS). The suitability of this machine in a proposed scenario (Chapter 1 to 4 and Appendix 3) was investigated. To adequately operate within the scenario, the system would need to operate without intervention for long periods, generating electricity into the national grid. Results from the study were mixed; the machine proved to have a good efficiency but there were problems with the stability of the gasification process and the filtration system. However, the study demonstrated that it is possible to gasify comminuted wood (wood chip). Modifications to the existing machinery have increased the effectiveness of the system, and problems were identified and solutions suggested (Chapter 4).

Theoretical analysis of the 30-kWe scenario, from establishment of the crop to the decommissioning of the crop and machinery, was carried out using crop and energy analysis models (LARS-Willow and Biomass Energy Analysis Program (BEAP)). The LARS-Willow model was used to calculate potential biomass production for willow in 26 locations within the UK. This information was used in the BEAP model to assess the Energy Rate of Return (ERR) at the 26 sites (Chapter 8). The ERRs calculated (ranging from 15 to 27) were favourable. The variation in these values is mainly due to changes in the cropping area because of variations in biomass yield.

The sensitivity of ERR to changes in a number of input parameters was also investigated. This sensitivity study showed that reductions in lifespan, increases in moisture content at harvest and increases in transportation distance adversely effected the ERR of the scenario. The significance of these effects varies, with changes in moisture content having little effect compared to increases in transport distance.

Yield data from the LARS-Willow model were used to provide a risk assessment of ERR based on yield variability due to climatic variation for the 26 sites, over a period of as near to 20 years as possible. Results form the risk assessment showed that all but 2 of the 26 sites had a 100% probability of reaching an ERR of 15 based on the predicted potential yield variations.

The BEAP model was used to investigate two case studies: a proposed 30-kWe gasifier scenario on a landfill site, and a 150 kW boiler system for heating a large farmhouse and swimming pool. The achievable ERRs for the landfill site were similar to those of the standard 30-kWe scenario. ERRs achievable for the 150 kW heating were much higher, ranging from 80 to 130 with yields of between 10 and 25 odt.ha^{-1}yr^{-1}. Again, sensitivity analysis was used to investigate both case studies.

The BEAP model was also used again in conjunction with the LARS-willow model to examine the effects that long term climate change could have on willow yields and therefore ERRs. Using a climate model and weather generator, climate variables were calculated for the period 2035 to 2054 for Rothamstead and Eskdalemuir. The changes in yield predicted by the LARS-willow model were not extreme and therefore the effect on the ERRs was to raise them by between 0 and 5 %.

The economics of a 30-kWe gasifier based system were investigated using a computer based model. This model used values for contract work for input variables as the scale on which a 30-kWe system would require farming would not warrant purchase of dedicated machinery.

The effect of variations in the price paid for generated electricity was studied as the output of the model. The model shows that for a small-scale 30-kWe gasifier system the electricity produced would need to be sold at 4 p/kWh for the system to make a profit in the best case scenario. For the worst case inputs this value rises to 9 p/kWh. Even in the best case the profitability is at best marginal even at the higher values. e.g. the total profit over 20 years at 11 p/kWh is £108,020 or approximately £5,000 per year.

CALCULATION OF ENERGY RATES OF RETURN FOR SMALL SCALE BIOMASS TO ENERGY SYSTEMS

A detailed investigation, with sensitivity and validation analysis, of a system based around the 30-kWe downdraft gasifier was done. A risk assessment investigated the effect that biomass yield variations had, due to climate variability, on ERRs in locations throughout the UK. A proposed system based around a 30-kWe unit and a heating system were also investigated. Finally, an investigation of the effects of climate change on yield and therefore ERRs was carried out.

30-KWE DOWNDRAFT GASIFIER BASED SYSTEM

GEOGRAPHICAL ANALYSIS AND ERR DETERMINATION

A standard scenario was drafted (Chapter 1,6 and Appendix 2). This 30-kWe downdraft gasifier scenario was investigated for a variety of biomass yields. The yields were chosen to either represent presently achievable values or from the potential yield modelling work in Chapter 7. For these values of yield an ERR was calculated for 26 sites around the UK.

Analysis of the 30-kWe scenario using BEAP showed that the two storage options (cooling-drying and direct drying) gave widely different results (Chapter 8). The direct drying option gave ERR values that were approximately 3 times higher than the cooling-drying method. Until recently, cooling-drying had been considered the best storage option for. The results from the BEAP analysis show that direct drying over a short period would be a better solution energetically. However, economic analysis of these different storage methods is unavailable so reaching a conclusion on their suitability is impossible. However, it is highly unlikely that a drop in ERR from 15.77 to 5.73 (figures based on 12 odt^{-1}ha^{-1}yr) will coincide with an increase in profitability. Therefore, direct drying was chosen for further investigation.

Analysis of the ERR for a given biomass yield using BEAP showed that for a given yield there is an optimum cropping area. This area minimises agricultural operations whilst producing enough fuel for the machine to run for its designed percentage of the year. These areas were calculated and used in the rest of the analysis.

For sites within the UK, ERR values of between 15.2 and 27.0 were calculated. These figures represent a favourable ERR value for electricity production. Comparisons with available data for ERRs from other forms of electricity production (Tsoulfanidis, 1981) show that these values are in excess of some of the established electricity production technologies (Table 1). No information on ERRs for gas-fired power stations could be found but it is the author's understanding that they are only slightly higher then those for coal fired generation.

Table 1. Comparison of values for ERR with potential yields and established electricity generating technologies.

Generating method	ERR
Biomass (30-kWe downdraft gasifier)	15 - 27
Coal	7
Nuclear-PWR (diffusion enrichment)	8
Nuclear-PWR (centrifuge enrichment)	13

The values in Table 1 for biomass are for potential yields at sites around the UK; these yields vary from 15.2 to 26.9 odt.ha^{-1}yr^{-1}. At present it is more likely that the actual yields will be lower (around 12 odt.ha^{-1}yr^{-1}). For lower yields, 10,12,14 and 16 odt.ha^{-1}yr^{-1}, values of ERR ranging from 10 to 16 were calculated. These values are still very favourable when considered against the values for established technologies listed in Table 1.

Since ERRs are linked to biomass yields they show a similar geographical trend to yields with ERRs highest in the south east of the UK and lowest in the far north. Apart from the south east of the country, there is a trend for higher ERRs on the western side of the country. This trend is due to climatic temperature, which tends to be higher in the west. The highest values for yield and biomass coincide with areas where conventional agriculture is widespread. It is in these areas that the potential for biomass production is highest if the economics of biomass to electricity could compete with food production.

Sensitivity analysis

As well as the ERR of a standard system, sensitivity to changes in a number of parameters will affect its feasibility. The sensitivity of ERR to changes in 6 parameters was calculated for the 30-kWe standard; from this it was possible to draw some conclusions as to the suitability of the system for the envisaged scenario.

Sensitivity analysis of changes in yield, for a number of different cropping areas, showed that for a given yield value there is an optimum area (the reasons for this have been discussed earlier). The decreases in ERR that result from increases in area for a constant biomass yield were highlighted in an analysis of the sensitivity of ERR to changes in area for 3 different yields. An increase of 50% in cropping area could lead to a decrease of approximately 20% in ERR in some cases. Decreases of this order would need to be avoided if possible. To do this a reliable estimate of yield for a proposed site was necessary.

In the analysis of the 30-kWe scenario a lifespan of 20 years was used. This is considered a good estimate of plantation and machinery lifespan. Twenty years is also a significant period over which to discount capital costs. The lifespan of a system could differ from this. The commitment necessary from a farmer for a 20 year lifespan may deter many prospective operators, whereas a community-based scheme might want to operate a system for longer. A sensitivity analysis of the effects of lifespan on the ERR of a system showed that as lifespan increases, the rate at which gains in ERR can be obtained from increases in lifespan decreases.

A decrease in lifespan from 20 years to 10 years would have the effect of lowering the ERR by approximately 30%. This would prejudice the feasibility of many systems. However an increase from 20 years to 30 years would have little effect, increasing the ERR by about 10%. The decrease in ERRs for lower lifespans supports the choice of 20 years as the standard. The fact that a commitment of such length is necessary for good ERRs will narrow the choice of farmers for prospective operators and, if recognised, will help target them better.

Transport distance is a variable that has been mooted to have a large effect on the ERR of a system. In the standard 30-kWe system used the transport distance is 0, since the system is set on a farm where the only transport necessary is from harvest to storage. Many possible systems would be needed to transport the fuel further. If a collection of farmers, each with a small area devoted to biomass crops, had a central shared unit the fuel would have to be transported to the conversion facility. If a conversion machine was being used by someone other than a farmer the fuel might have to be transported from the supplier. In instances like these the sensitivity of the ERR to transport distance would be an important factor in the selection of site or supplier. The analysis in this study showed that, as mooted, increases in transport distance have a significant detrimental effect on the ERR of a system. An increase from 0 to 60 km (37 miles) in transport distance approximately halves the ERR of the system. This will have significant effects on any system which considers importing fuel from a distance.

Two other parameters which might affect the feasibility of the system were the moisture content at harvest and the percentage of the year that the system operates. Changes in both these variables produced a noticeable effect, with increases in the former and decreases in the latter lowering the ERR.

Decreases in the percentage of the year the machine operated affected the ERR surprisingly little. The economics of the system would dictate that the system would run for as long as possible. Consequently the period for which the system was operated would not vary much and the variability of ERR within this band would be small.

Moisture content at harvest is also a parameter, which in the standard system would vary little. The effect it can have on the ERR is more pronounced than the effects of changes in period of operation. However, it would not significantly affect a decision on the feasibility of the system.

RISK ASSESSMENT

A risk assessment investigated the effect that variation in yield, predicted by potential yield modelling, would have on the ERR of the 30-kWe scenario. The yield of the crop is the only part of the system that could not be controlled. Variations in climate will inevitably lead to years of low production. An assessment of the risk this poses to the potential ERR of the system is important in deciding whether to go ahead with a system at a location.

The variations in potential biomass yield were not extreme due to the non-inclusion of water and nutrient stress in the crop modelling. However, the variations are similar to those that might be expected with a well-managed crop, in a suitable location. The variations had an effect but did not affect the possible ERRs enough to make many of the areas investigated unfeasible. All but 2 of the 26 sites investigated have a probability of achieving an ERR of above 15 of 1 (i.e. every year) and 50% of the sites have a probability of 1 of obtaining an ERR of 17. These probabilities show that the variations in potential production would not lower the ERR at most of the sites to a level where feasibility is in question. They also show that most of the sites will continuously operate at a good level of ERR.

Geographical trends of probability, like geographical trends in average ERR, are due to climate. However, whereas the trend for average ERR was towards higher values in the south east of the country, the higher probabilities for a given ERR are in the south west of the country. This is due to the more temperate climate in the south west compared to the south east. Similarly, trends in average ERR in sites in the north of the country are less favourable.

CASE STUDIES

To further investigate small-scale biomass power systems and investigate the flexibility of BEAP, two systems other than the 30-kWe standard system were investigated (Chapters 6,8 and Appendix 2):

- A system using the 30-kWe downdraft gasifier, under investigation at LARS, as an electricity producer on a disused landfill site (proposed by Terry Adams Ltd).

- A system based around a 150 kW heating boiler based on an existing system (run by Lionel Hills and Sons).

The landfill site system gave similar results to the standard 30-kWe scenario with ERRs ranging from 14.92 to 22.09, depending on the biomass yield and the cropping area used. The lowest yield figures used were 14 $odt.ha^{-1}yr^{-1}$ and represent a realistic estimate on which to calculate the ERR for this site (14.92). This value is favourable and higher yields should be possible making the planned system more energetically attractive.

The Talbott/Hills heating system gave significantly different results from the landfill and standard systems. The efficiency gains from using the fuel for heating, and the fact that the fuel was a by-product of a cuttings business led to much higher ERR values (100.69 to 137.54, dependent on yield). These values are exceptionally favourable and add to evidence showing heating plants to be a good option for similar institutions.

Sensitivity analysis, similar to that of the standard 30-kWe scenario, was carried out on both the above systems. The order of sensitivity of both systems was similar to that of the standard system although the figures varied (considerably for the Talbott/Hills scenario). In both the Talbott/Hills scenario and the standard scenario the systems have constraints on their operation. Within these constraints the sensitivity to the variables studied would not affect the conclusion that the ERRs for both systems are good.

The affect of possible changes in the environment on ERRs was also investigated. Using a weather generator, data for two sites were calculated. This is daily weather data generated on a per site basis. This data incorporates the affect that changes in CO_2 in the atmosphere will have on the current values. This data was then fed into the crop and energy models that were developed. The data from this analysis shows that the changes in crop yield (although noticeable) will not have a significant effect on the ERR of a proposed system. As a result the conclusion of the analysis of ERRs, that they are favorable, from the using observed weather data is not changed.

EFFECTS OF CLIMATE CHANGE ON WILLOW YIELD AND THEREFORE ERRS

Using a model developed by Semenov *et.al.* (1997) values for solar radiation, temperature etc. were produced for a period between 2035 and 2054 for two sites within the UK. These sites, chosen to represent the two ends of the country geographically, were Rothamstead and Eskdalemuir. For this period the LARS-willow model was used to generate potential yields and these yield values were used to calculate potential ERRs.

Changes in yield between current climate and future climate were between 0.4 and 1.9 odt.ha^{-1}yr^{-1}. These represent a change of between 1.7 and 10.6 %. When these values are used to calculate ERRs the changes they produce are between 0 and 5 %. This is not a significant change in the ERR and does not represent a change which would affect the conclusions on feasibility dependant on ERR.

PRACTICAL AND NON-TECHNICAL FACTORS AFFECTING THE FEASIBILITY OF SMALL-SCALE BIOMASS TO ENERGY

PRACTICAL ASSESSMENT OF THE FEASIBILITY OF THE 30-KWE DOWNDRAFT GASIFIER SYSTEM AT LARS

The gasifier system in use at LARS (Chapter 3) was designed to work as a stand-alone system, producing electricity from wood blocks. The envisaged scenario (Chapters 1,3 and Appendix 2) would require the gasifier to operate on wood chip, producing electricity into the national grid. This represents a significant change in the proposed use. Modification for running on wood chip proved problematical. Once the gasifier could be run on wood chip, it proved to be efficient and operated with little or no tar production. However achieving stability in the reactions, which would allow constant electricity generation to the national grid, was a problem.

EFFICIENCY OF GASIFICATION AND GENERATING PROCESS

The ratio of energy out (electricity) to energy input (available energy stored in the wood fuel) will determine the efficiency of the gasifier. It was calculated that 1 tonne of wood chip equates to

2.976×10^9 J of electricity (Chapter 4). If wood chip is assumed to have a calorific value of 20 $MJ.kg^{-1}$ (Matthews *et al.*, 1994) then the efficiency of the gasifier is 14.88 %; this is a good efficiency figure for a small-scale electricity generating process.

CHIP FLOW

The wood fuel for gasification is stored in a hopper prior to conversion. The fuel must flow unobstructed downwards through the gasifier and hopper to the conversion zones if the system is to operate stably and continuously. Wood chip, covered in tars from pyrolysis, had a tendency to form bridges within the hopper. This halts the chip flow and thus the gasification process. A system of two vibrating bars, hanging down through the hopper, intermittently agitating the wood chip was adopted. This method seemed to work effectively.

The size of the hopper limits the length of continuous operation to two hours. If the gasifier were to be used in the scenario envisaged, this would not be enough; a system of automated fuel feeding would have to be included.

HEARTH GEOMETRY

The hearth geometry of the gasifier in use at LARS was modified a number of times in an attempt to arrive at a set of optimum dimensions. The geometry of the air inlets and the throat (hearth) appear suitable for both the fuel and the rating of the system. Investigation of the pipe-work and filtration system showed little evidence of tar build-up. This led the author to conclude that the temperature at the throat was kept suitably high and was relatively uniform across the area of the throat.

The reduction zone geometry caused problems. The design of the grate and depth of the reduction zone were modified many times. At extremes of high and low reduction zone depth, the system refused to function for anything other than a short period and at depths between these two extremes, there were problems. Frozen reduction, or a build up of ash, blocked the grate after a while, whatever the depth of the hearth. The only way of removing this blockage was to riddle the grate. A mechanical device was developed that moved the grate up and down, unblocking it. If the grate was excessively riddled then too much material fell through and the gas produced subsequently was not of a high enough quality. Attempts to arrive at a method for operating the mechanical riddler on a time-off – time-on basis failed since the system was unpredictably unstable. An operator with prior knowledge of the machine was able to control the process by judging the riddling action necessary from pressure readings at the blast tube.

FILTRATION CHAIN

The efficiency of the filtration chain defied quantifying statistically. However, operator observation led to a number of conclusions regarding its effectiveness. On short runs, i.e. under 2 hours, the filtration chain operated effectively and each of the filtration components removed the particles for which it was designed. However, on longer runs the effectiveness of the filtration chain as a whole dropped significantly.

Once the collection zones within the filtration components were full, they stopped removing particles from the gas flow. The particles were then carried further into the filtration system until they came to rest in the cooler. As the particles collected in the cooler, its ability to remove water from the gas flow was reduced and resistance to gas flow increased. Most of the water condensed in the sawdust and foam filter, further increasing the resistance to gas flow. This increase did not reach a point where it would shut down the gasification-generating process. However, it did reduce the degree of flexibility that the gasifier had to respond to changes in demand for gas from the generator.

THE GENERATOR

Investigation and modification of the generator was limited, and for the purpose of the study it was considered a black box system. However, the dismantling of some of the generator components allowed some conclusions to be made about the cleanliness of the gas reaching the generator.

Removal of the spark plug for examination led to the conclusion that the gas supplying the engine was of a good quality and clean. The butterfly valve of the gas carburettor was removed at intervals and examined. In certain circumstances some carbon particles, and a small quantity of tar, were reaching the engine and building up on the butterfly valve. However, investigation of the pipe-work leading to the engine showed little build-up of tar or particles indicating the quantity was low. There appeared to be no adverse effects on the operation of the engine-generator system due to this.

ECONOMIC ASSESSMENT OF SMALL-SCALE BIOMASS TO ENERGY

In addition to the two main studies in this work (practical and energetic analyses) an economic analysis of the proposed 30-kWe scenario was undertaken.

A model was developed to look at the profitability of a 30-kWe scenario over a 20 year lifespan. This model used contract values for inputs since it was assumed that the scale of production would not justify the purchase of agricultural machinery solely for this system. Two sets of values were used for input based upon different values available from literature and personal communications. These two sets have been labelled best case and worst case, with the best case values being the lowest cost inputs. The profits are discounted to represent the overall profit in current terms.

With the best case values the system becomes profitable at about 4 p/ kWh. In the worst case this value rises to 9 p/kWh. In both cases the profitability at this level is minimal. The best profitability calculated was for the best case values at 11 p/ kWh, this gives an overall profit of £108,020 over 20 years. This is approximately £5,000 per year.

At this level of profitability it is unlikely that small-scale systems will prove profitable even with the inclusion of the benefits available from the NFFO scheme. It would also take a high level of carbon taxation to make such a system competitive.

CONCLUSIONS ON THE SUITABILITY OF A SMALL-SCALE BIOMASS TO ELECTRICITY SCENARIO BASED ON A 30-KWE DOWNDRAFT GASIFIER GENERATING SYSTEM

When considering the suitability of small-scale biomass energy production using a system similar to the one described in this work, three questions must be answered. Firstly, the question of the theoretical suitability of small-scale biomass to energy system. This has been addressed in this work by energy analysis. Secondly, the question of whether it is possible to produce energy reliably from biomass on a small scale. This has been addressed with analysis on a small downdraft gasifier system. Thirdly a question must be posed about the social, political and economic suitability of biomass to electricity on this scale. This is much harder to answer as it is dependent on factors that cannot be adequately predicted.

The energy analysis work undertaken has shown that the ERRs achievable from the proposed scenarios are favourable, compared with existing electricity generating technologies, even with low yields. As cultivation techniques progress and new clones of willow are developed, the ERRs will become more favourable. The fact that the ERRs of this technology are greater than those of existing technologies combined with the beneficial environmental effects of biomass energy should lead to more research into this field. The aim of this research should be to overcome the non-technical factors which are hindering implementation.

The practicality of small-scale energy from biomass is not as clear-cut. The 30-kWe gasification unit studied in this work is not at a stage where it could be implemented in a commercial situation. Problems with stability, filtration and automation still have to be addressed. However the work here has, in the author's opinion, shown that there is a significant probability that these problems could be overcome and that the system as it stands has a good efficiency. It must be noted that others working in the same field do not hold the view that the technical factors can be overcome. Concern has been expressed that the size of the unit will limit the possibility of reaching suitable stable chemical reactions (Dawson, 1998). There are also concerns that the level of automation necessary would lead to an overly complicated and therefore too expensive, design. The author does not believe this to be the case, however more work is necessary if these problems are to be discounted.

The economic profitability of the 30-kWe system is not good. Even with the best case analysis it is marginally profitable at prices that far exceed those available for electricity at present. Carbon taxation and/or subsidisation could affect this conclusion but from the results it can be seen that the level at which taxation would need to be set or subsidisation given would have to be very high.

There is significantly more room for development in the technical aspects of biomass energy production than in the more traditional technologies and this may affect the profitability significantly. However, a change in political and governmental policy is necessary if these types of systems are to be helped to compete with traditional energy sources.

THE FUTURE FOR SMALL SCALE BIOMASS

The technical problems associated with small-scale biomass energy production can be overcome. The energetic profitability (ERR) of such systems is better than that of popular methods of electricity production. So why is biomass not an option which is being put into use? The answer of course is that the economics of such systems does not make sense at present.

The economics of biomass will become the most important factor in its implementation and unless this can be addressed there is little likelihood of large scale adoption of the technology. To make biomass on this scale economic either the costs of production must decrease or the price paid for electricity must increase. It is unlikely that significant decreases in the cost of production will occur, although this cannot be ruled out. It is most probable that economic profitability will come from an increase in electricity prices.

In the long term (this maybe over 20 years away) it is almost certain that prices for fossil fuels will increase. This increase could happen for a number of reasons. Fossil fuels as supplies will become harder to extract both technically and politically, slowly the resources of fossil fuels will decrease, demand will rise as underdeveloped nations develop, etc. It is at this point that biomass energy and other forms of renewable energy may be able to compete.

Socially there are factors which could also affect the economics of such systems. In Holland there are increasing numbers of people who are opting to pay premium prices for 'green' electricity. Schemes like this are being adopted in other European countries (e.g. Ireland) and if they continue to grow in popularity there will be a need for a renewable energy source more dependable than the wind power, which is most commonly used at present. Biomass could get a significant boost by providing this energy.

It is also possible that governments may move to implement more beneficial subsidisation schemes or implement taxation strategies which charge for the use of non-renewable resources. Although from the economic analysis in this work it can be seen that rates for subsidisation and taxation would have to be very high.

Taking into account all the factors which will affect the economics in the future is a difficult task. However it seems possible that the energy market place could support biomass in the future, even if this is 20 years away. The energetic profitability of this technology should, at least, keep it in the running.

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APPENDIX 1

CALCULATION OF ENERGY INPUTS TO BIOMASS TO ENERGY SYSTEMS

AGRICULTURAL OPERATIONS

DIRECT ENERGY USE

The energy use of agricultural operations has been calculated using a method adopted by Mathews *et al.* (1994).

U_d	= direct energy use per ha	($MJ.ha^{-1}$)
hp	= horse power necessary to carry out operation	(hp)
t	= time per ha for operation	(h)
FU	= fuel use for unit of work	($l.hp^{-1}.h^{-1}$)
OU	= oil use for unit of work	($l.hp^{-1}.h^{-1}$)
E_f	= energy content of fuel	($MJ.l^{-1}$)
E_o	= energy content of oil	($MJ.l^{-1}$)

$$U_d = hp \times t\left(\left(FU \times E_f\right) + \left(OU \times E_o\right)\right) \quad (1)$$

Values for FU and OU are summarized in Table 1.

Table 1. Estimated values for oil and fuel use (Matthews et al.*, 1994).*

	High Estimate ($l.hp^{-1}.h^{-1}$)	Low estimate ($l.hp^{-1}.h^{-1}$)
Fuel Use (FU)	0.3	0.2
Oil Use (OU)	0.001	0.0004

Values for Ef and Eo are 43.38 $MJ.l^{-1}$ and 41.93 $MJ.l^{-1}$ respectively (Matthews *et al.,* 1994). Both these values take account of indirect energy associated with the fuel as well as its calorific value.

Values for hp and t are summarized in Table 2, with the calculated $MJ.ha^{-1}$ fuel and oil use and the total $MJ.ha^{-1}$ energy use for the particular operation. The table is divided into three sections for high, medium and low estimates.

Table 2. Direct energy use for agricultural operations

Function	horse power used* (hp)	Time per ha (hrs)†	Fuel use ($MJ.ha^{-1}$)	Oil use ($MJ.ha^{-1}$)	Total ($MJ.ha^{-1}$)
High					
Sprayer	40	0.229	118.99	0.383	119.38
Fertilizer applicator	50	0.400	260.29	0.838	261.14
Plough	85	1.600	1770.02	5.702	1775.72
Harrow	75	0.667	650.74	2.096	652.84
Rotovator	85	2.000	2212.52	7.128	2219.65
Step planter††	80	0.800	832.95	2.683	835.63

Forage harvester†*	297	0.706	2733.63	8.806	2742.44
Loughry harvester**	75	16.000	15617.84	50.313	15668.15
Medium					
Sprayer	40	0.128	55.530	0.215	55.74
Fertilizer applicator	50	0.320	173.53	0.671	174.20
Plough	85	1.142	1053.58	4.073	1057.66
Harrow	75	0.667	542.28	2.096	544.38
Rotovator	85	1.600	1475.01	5.702	1480.72
Step planter	80	0.800	694.12	2.683	696.81
Forage harvester	255	0.706	1952.59	7.548	1960.14
Loughry harvester	55	16.000	9544.23	36.896	9581.13
Low					
Sprayer	40	0.145	50.48	0.097	50.58
Fertilizer applicator	50	0.267	115.68	0.223	115.91
Plough	85	0.889	655.56	1.267	656.83
Harrow	75	0.667	433.82	0.838	434.67
Rotovator	85	1.333	983.34	1.900	985.25
Step planter	80	0.800	555.30	1.073	556.37
Forage harvester	212	0.706	1301.73	2.516	1304.24
Loughry harvester	31	16.000	4303.58	8.318	4311.90

* (Matthews *et al.*, 1994).
† (Nix, 1996).
**. (Neale and Reed, 1992).
††. Direct measurement.
†*. (Claas UK, 1996).

INDIRECT ENERGY USE

Similarly to direct energy use, indirect energy use can be calculated for individual agricultural operations.

U_i	= indirect energy use	($MJ.ha^{-1}$)
E_i	= indirect energy content of material or machine	($MJ.kg^{-1}$)
E_{maint}	= energy cost of maintenance	($MJ.h^{-1}$)
M_{imp}	= mass of implement or machine	(kg)
t	= time per ha for operation	(h)
Lifespan	= serviceable lifespan of machine	(h)

$$U_i = \left(\frac{(E_i \times M_{imp}) + E_{maint}}{Lifespan} \right) \times t \qquad (2)$$

Table 3 summarises the calculations made using Equation (2 for the agricultural operations under consideration. The table is separated into high, medium and low estimates.

Table 3 Calculations for indirect energy use for agricultural operations (Matthews et al., *1994).*

Function	Weight tonnes		$MJ.kg^{-1}$		Lifespan	Maintenance $MJ.hr^{-1}$		Total $MJ.ha^{-1}$
	T*	I**	T	I		T	I	
High								
Sprayer	4.0	500	115	115.0	5000	0.005	0.001	23.66
Fertiliser-applicator	4.0	500	115	115.0	5000	0.005	0.001	41.40
Plough	4.0	1200	115	66.1	5000	0.005	0.001	172.59
Harrow	4.0	1400	115	66.1	5000	0.005	0.001	73.68
Rotovator	4.0	1400	115	66.1	5000	0.005	0.001	221.03
Step planter	4.0	1120	115	66.1	13000	0.005	0.001	32.87
Forage-harvester	0.0	8000	115	115.0	8000	0.000	0.015	81.20

Loughry-harvester	4.0	3580	115	115.0	8000	0.005	0.01	1743.64
Medium								
Sprayer	2.6	400	115	115.0	10000	0.005	0.001	4.42
Fertiliser- applicator	2.6	400	115	115.0	10000	0.005	0.001	11.04
Plough	2.6	1000	115	66.1	10000	0.005	0.001	41.73
Harrow	2.6	1000	115	66.1	10000	0.005	0.001	24.34
Rotovator	2.6	1300	115	66.1	10000	0.005	0.001	61.60
Step planter	2.6	1120	115	66.1	13000	0.005	0.001	22.96
Forage-harvester	0.0	7000	115	115.0	13000	0.000	0.015	43.73
Loughry-harvester	2.6	3580	115	115.0	13000	0.005	0.015	875.03
Low								
Sprayer	1.2	300	115	115.0	10000	0.005	0.001	2.51
Fertilizer –applicator	1.2	300	115	115.0	10000	0.005	0.001	4.60
Plough	1.2	700	115	66.1	10000	0.005	0.001	16.38
Harrow	1.2	700	115	66.1	10000	0.005	0.001	12.29
Rotovator	1.2	1200	115	66.1	10000	0.005	0.001	28.98
Step Planter	1.2	1120	115	66.1	13000	0.005	0.001	13.05
Forage-harvester	0.0	7000	0	115.0	13000	0.000	0.015	43.73
Loughry-harvester	1.2	3580	115	115.0	13000	0.005	0.015	676.87

* Tractor
** Implement

TRANSPORT

DIRECT ENERGY USE

Using a method adopted by Matthews *et al.* (1994) it can be shown that if k is a constant

$$U_d = hp \times k\left(\left(FU \times E_f\right) \times \left(OU \times E_o\right)\right) \qquad (3)$$

The constant k is dependent on the average speed of the transporter, the bulk density of the goods transported and the volume of the transporter. Calculations for two different sizes of transporter are summarised in Table 4.

Table 4. Direct energy use for road transporter's (Matthews et al., *1994).*

Function	hp	k	Fuel use MJ.km^{-1}	Oil use MJ.km^{-1}	Total MJ.km^{-1}
High					
55 m^3 road transport	292.5	0.006	21.24	0.068	21.31
80 m^3 road transport	292.5	0.004	14.61	0.047	14.66
Medium					
55 m^3 road transport	192.5	0.006	11.64	0.045	11.69
80 m^3 road transport	192.5	0.004	8.01	0.031	8.05
Low					
55 m^3 road transport	135	0.006	6.53	0.013	6.55
80 m^3 road transport	135	0.004	4.49	0.009	4.51

INDIRECT ENERGY USE

Calculation of indirect energy use for transport uses the same equation as for agricultural operations (2). The results of the indirect energy calculations for transport are summarised in Table 5.

Table 5. Indirect energy use for road transport's (Matthews et al., *1994).*

Size	Weight (kg)	MJ.kg^{-1}	Lifespan (hrs)	hrs.km^{-1}	MJ.km^{-1}	Maintenance	Total MJ.km^{-1}

						hrs.km^{-1}	MJ.hr^{-1}	
High								
55 m^3	10000	115	8000	0.0056	0.80	0.00558	0.015	0.80
80 m^3	13000	115	8000	0.0038	0.72	0.00384	0.015	0.72
Medium								
55 m^3	10000	115	13000	0.0056	0.49	0.00558	0.015	0.49
80 m^3	13000	115	13000	0.0038	0.441	0.00384	0.015	0.44
Low								
55 m^3	10000	115	13000	0.0056	0.49	0.00558	0.015	0.49
80 m^3	13000	115	13000	0.0038	0.44	0.00384	0.015	0.44

CONVERSION MACHINERY

DIRECT ENERGY USE

Two types of conversion machine have been used in the modelling work. Values for direct energy consumption for the 30-kWe downdraft gasifier were obtained by measurement. Values for the Talbott hills boiler were obtained from Talbot's.

Values for the 30-kWe gasifier come from the rated wattage of the electrical components. Since the start-up fan and the fuel shaker are only on for a very limited time they do not have a significant effect on the energy consumption of the conversion machine.

Table 6. Power use of 30-kWe gasifier system.

Component	Wattage
Cooling fans	432
Start-up fan	960
Shaker	960

Values for direct energy use for both systems are summarised in Table 7.

Table 7. Direct energy use of conversion machines

Conversion machine	Energy use MJ.hr^{-1}	Source
30-kWe gasifier	2.98	Direct measurement
Talbott boiler	14.40	(Talbott, 1996/1997)

INDIRECT ENERGY USE

Using Equation (2) the indirect energy use of the conversion machines can be calculated (Table 8).

Table 8. Indirect energy use of conversion machines.

Conversion machine	Weight (kg)	MJ.kg^{-1}	Lifespan	MJ.hr^{-1} maintenance	Total MJ.hr^{-1}
30-kWe gasifier	900	66.1	122640	0.01	0.49
Talbott boiler	3000	66.1	101616	0.01	1.96

MISCELLANEOUS OPERATIONS

The are two operations used in the model, which did not fall into one of the above categories: tractor-trailer transport and independent chipping. Using the same equations as were used in the agricultural operations ((1)(2)) values are obtained (Table 9 and Table 10).

Table 9. Direct energy use for chipping and transport on farm.

Function	hp	Time ($h.odt^{-1}$)	Fuel use	Units	Oil use	Units	Total	Units
High								
Tractor + trailer	40	N/A	520.6	$MJ.hr^{-1}$	1.68	$MJ.hr^{-1}$	522.3	$MJ.hr^{-1}$
Independent chipper	212	0.4	1106.3	$MJ.odt^{-1}$	3.56	$MJ.odt^{-1}$	1109.8	$MJ.odt^{-1}$
Medium								
Tractor + trailer	40	N/A	433.8	$MJ.hr^{-1}$	1.68	$MJ.hr^{-1}$	435.5	$MJ.hr^{-1}$
Independent chipper	170	0.275	507.0	$MJ.odt^{-1}$	1.96	$MJ.odt^{-1}$	509.0	$MJ.odt^{-1}$
Low								
Tractor + trailer	40	N/A	347.1	$MJ.hr^{-1}$	0.67	$MJ.hr^{-1}$	347.7	$MJ.hr^{-1}$
Independent chipper	127	0.15	165.9	$MJ.odt^{-1}$	0.32	$MJ.odt^{-1}$	166.3	$MJ.odt^{-1}$

Table 10. Indirect energy use of chipping and transport by trailer.

Function	Weight (kg)		$MJ.kg^{-1}$		Lifespan (hrs)	$hrs.odt^{-1}$	$MJ.hr^{-1}$		Total
	T*	I†	T	I			T	I	
High									
Tractor + trailer	4000	1200	115	66.1	5000		0.001	0.005	107.9 $MJ.hr^{-1}$
Independent chipper	0	7500	115	66.1	8000	0.400	0.005	0.000	24.8 $MJ.odt^{-1}$
Medium									
Tractor + trailer	2600	1200	115	66.1	10000		0.001	0.005	37.8 $MJ.hr^{-1}$
Independent chipper	0	7000	115	66.1	13000	0.275	0.005	0.000	9.8 $MJ.odt^{-1}$
Low									
Tractor + trailer	1200	1200	115	66.1	10000		0.001	0.005	21.7 $MJ.hr^{-1}$
Independent chipper	0	6000	0	66.1	13000	0.150	0.005	0.000	4.6 $MJ.odt^{-1}$

*. Tractor.
†. Implement.

STORAGE AND DRYING

There has been little research into the storage and drying of wood fuel, so information on energy consumption is sparse. Table 11 summarises the values that have been used in the modelling in this research. Cooling describes the constant aeration of the fuel with ambient air. The drying figures are for a situation where the fuel is dried using imported heat and constant aeration.

Table 11. Values for cooling and drying of wood chip (Nellist, 1994)

Method	Energy use $GJ.t^{-1}$ of evaporated water
Cooling	0.87
Drying	0.05

MATERIALS DATA

As well as the energy associated with mechanical operations, energy is consumed with the use of materials within a system. Values for materials used are summarised Table 12.

Table 12. Values for energy content of materials (Matthews et al., *1994).*

Material	Energy content	Unit
Herbicides/Insecticides/Fungicides	106.0000	$MJ.kg^{-1}$ active ingredient
Fertilizer	28.7000	$MJ.kg^{-1}$ active ingredient
Cuttings	0.0879	$MJ.cutting^{-1}$
Fences	47.5000	$MJ.m^{-1}$
Buildings	6.7000	$MJ.m^{3-1}$

INPUT TABLES

The data calculated above has been compiled into the following tables for input into the biomass energy analysis program.

PROCESS DATA

MAXIMUM

Operation	Direct use ($MJ.ha^{-1}$)	Indirect use ($MJ.ha^{-1}$)
Tractor + trailer	522.272	107.870
Tractor + sprayer	119.376	23.658
Tractor + fertiliser applicator	261.136	41.402
Tractor + plough	1775.724	172.592
Tractor + harrow	652.840	73.676
Tractor + rotovator	2219.655	221.028
Step planter	835.634	32.868
Forage harvester	2742.441	81.202
Loughry harvester	15668.150	1743.640
Stand alone chipper	1109.827	24.789
55 m3 transporter (road)	21.310	0.802
80 m3 transporter (road)	14.665	0.718
30-kWe Gasifier	2.9808	0.485

AVERAGE

Operation	Direct use ($MJ.ha^{-1}$)	Indirect use ($MJ.ha^{-1}$)
Tractor + trailer	435.506	37.838
Tractor + sprayer	55.745	4.417
Tractor + fertiliser applicator	174.202	11.042
Tractor + plough	1057.657	41.733
Tractor + harrow	544.382	24.344
Tractor + rotovator	1480.720	61.598
Step planter	696.809	22.961
Forage harvester	1960.144	43.729
Loughry harvester	9581.130	875.027
Stand alone chipper	508.997	9.789
55 m3 transporter (road)	11.695	0.494
80 m3 transporter (road)	8.028	0.442
30-kWe Gasifier	2.981	0.485

MINIMUM

Operation	Direct use ($MJ.ha^{-1}$)	Indirect use ($MJ.ha^{-1}$)
Tractor + trailer	347.734	21.738

Tractor + sprayer	50.579	2.510
Tractor + fertiliser applicator	115.911	4.602
Tractor + plough	656.831	16.385
Tractor + harrow	434.667	12.289
Tractor + rotovator	986.246	28.984
Step planter	556.374	13.053
Forage harvester	1304.247	43.729
Loughry harvester	4311.900	676.874
Stand alone chipper	166.260	4.577
55 m3 transporter (road)	6.549	0.494
80 m3 transporter (road)	4.520	0.442
30-kWe Gasifier	2.981	0.485

MATERIALS DATA

Material	MJ/unit	units
Herbicides	1.06E+08	Kg
Pesticides	1.06E+08	Kg
Fertiliser	28700000	Kg
Cuttings	87900	
Fence	47500000	m
Storage building	6666666	m^3
Conversion building	6666666	m^3

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APPENDIX 2.

DESCRIPTION OF 30-KWE SCENARIO AND CASE STUDY'S USED IN BEAP WORK

30-KWE GASIFIER SCENARIO

Variable	Units	Value
GENERAL		
Rotation period	yrs	3
Yield	odt.ha^{-1}	Variable
Available area for crop	ha	Variable
Quantity of fuel necessary to run machine for a year	tonnes (wet)	297.8
ESTABLISHMENT		
Quantity of herbicide used	kg.ha^{-1}	4.87
Quantity of fertiliser used	kg.ha^{-1}	0
Planting density	Cuttings.ha^{-1}	10,000
Fence type		0
Fence perimeter length	m	N/A
MANAGEMENT		
Quantity Of herbicide used	kg.ha^{-1}	4.87
Quantity Of fertiliser used	kg.ha^{-1}	0
Year in which herbicide is applied first	yr.	3
Interval in herbicide application	yrs	3
Year in which fertiliser is applied first	yr.	0
Interval in fertiliser application	yrs	0
HARVESTING		
% of crop lost during harvesting	%	0
Distance travelled by tractor and trailer to unload harvest	km	1.5
Capacity of trailer	tonnes	8
TRANSPORT		
Distance between field and storage site	km	0
Vehicle capacity	T	0
STORAGE		
Moisture content of crop when harvested	%	46
Moisture content of fuel when ready for Conversion	%	15
Loss of mass during drying	%	3.54
Volume of drying facilities	m^3	Variable
% Heat taken from conversion used in storage	%	0
Storage/drying building size	m^3	Variable
Storage/drying building type	m^3	1
Volume per tonne of wood chip	m^3	0.045
CONVERSION		
Joules of electricity per tonne of fuel	J	2.9×10^9
Joules of heat per tonne of fuel	J	5.9×10^9
Conversion building size	m^3	103
Conversion building type	m^3	1
Size of conversion machines	m^3	102.87
% of heat from conversion used	%	0
% of electricity from conversion used	%	100
% of the year that the conversion machine operates	%	70
% of required mass necessary to make it worth operating a machine	%	50
DECOMMISSIONING		
Quantity of herbicide used in decommissioning	kg.ha^{-1}	4.87
Lifespan of plantation	yrs.	20

OPERATION	Est.	Man.	Harv.	Trans.	Stor.	Conv.	Dcom.
Tractor + trailer	1	0	1	0	0	0	0
Tractor + sprayer	1	1	0	0	0	0	1
Tractor + fertiliser applicator	0	0	0	0	0	0	0
Tractor + plough	1	0	0	0	0	0	0
Tractor + harrow	1	0	0	0	0	0	0
Tractor + rotovator	0	0	0	0	0	0	1
Step planter	1	0	0	0	0	0	0
Harvesting *	0	0	2	0	0	0	0
Stand alone chipper	0	0	0	0	0	0	0
Storage handler	0	0	0	0	0	0	0
JCB	0	0	0	0	0	0	0
Transport♥	0	0	0	0	0	0	0
Transport by rail	0	0	0	0	0	0	0
Conversion**	0	0	0	0	0	1	0
Drying♥♥	0	0	0	0	2	0	0

*Loughry harvester = 1: Forage harvester = 2.

♥55 m^3 transporter (road) = 1: 80 m^3 transporter (road) = 2.
**30kWe gasifier = 1: Talbott boiler =2.

♥♥ Drying not using energy = 1: Drying = 2; Cooling and drying =3.

TERRY ADAMS SCENARIO

Variable	Units	Value
GENERAL		
Rotation period	yrs	3
Yield	odt.ha^{-1}	Variable
Available area for crop	ha	19
Quantity of fuel necessary to run machine for a year	tonnes (wet)	297.83
ESTABLISHMENT		
Quantity of herbicide used	kg.ha^{-1}	4.87
Quantity of fertiliser used	kg.ha^{-1}	0
Planting density	Cuttings.ha^{-1}	10,000
Fence type		0
Fence perimeter length	m	N/A
MANAGEMENT		
Quantity Of herbicide used	kg.ha^{-1}	4.87
Quantity Of fertiliser used	kg.ha^{-1}	0
Year in which herbicide is applied first	yr.	3
Interval in herbicide application	yrs	3
Year in which fertiliser is applied first	yr.	0
Interval in fertiliser application	yrs	0
HARVESTING		
% of crop lost during harvesting	%	0
Distance travelled by tractor and trailer to unload harvest	km	1.5
Capacity of trailer	tonnes	8
TRANSPORT		
Distance between field and storage site	km	0
Vehicle capacity	T	0
STORAGE		
Moisture content of crop when harvested	%	46
Moisture content of fuel when ready for Conversion	%	15
Loss of mass during drying	%	3.54
Volume of drying facilities	m^3	Variable
% Heat taken from conversion used in storage	%	0
Storage/drying building size	m^3	Variable
Storage/drying building type	m^3	1
Volume per tonne of wood chip	m^3	0.045
CONVERSION		

Joules of electricity per tonne of fuel	J	2.9×10^9
Joules of heat per tonne of fuel	J	5.9×10^9
Conversion building size	m^3	103
Conversion building type	m^3	1
Size of conversion machines	m^3	102.87
% of heat from conversion used	%	0
% of electricity from conversion used	%	100
% of the year that the conversion machine operates	%	70
% of required mass necessary to make it worth operating a machine	%	50
DECOMMISSIONING		
Quantity of herbicide used in decommissioning	$kg.ha^{-1}$	0
Lifespan of plantation	yrs	20

OPERATION	Est.	Man.	Harv.	Trans.	Stor.	Conv.	Decom.
Tractor + trailer	1	0	1	0	0	0	0
Tractor + sprayer	1	1	0	0	0	0	1
Tractor + fertiliser applicator	0	0	0	0	0	0	0
Tractor + plough	1	0	0	0	0	0	0
Tractor + harrow	1	0	0	0	0	0	0
Tractor + rotovator	0	0	0	0	0	0	1
Step planter	1	0	0	0	0	0	0
Harvesting *	0	0	2	0	0	0	0
Stand alone chipper	0	0	0	0	0	0	0
Storage handler	0	0	0	0	0	0	0
JCB	0	0	0	0	0	0	0
Transport▼	0	0	0	0	0	0	0
Transport by rail	0	0	0	0	0	0	0
Conversion**	0	0	0	0	0	1	0
Drying▼▼	0	0	0	0	2	0	0

*Loughry harvester = 1: Forage harvester = 2.

▼55 m^3 transporter (road) = 1: 80 m^3 transporter (road) = 2.

**30-kWe gasifier = 1: Talbott boiler =2.

▼▼ Drying not using energy = 1: Drying = 2; Cooling and drying =3.

TALBOTT/HILLS SCENARIO

Variable	Units	Value
GENERAL		
Rotation period	yrs	3
Yield	$odt.ha^{-1}$	Variable
Available area for crop	ha	6
Quantity of fuel necessary to run machine for a year	tonnes (wet)	245.28
ESTABLISHMENT		
Quantity of herbicide used	$kg.ha^{-1}$	4.87
Quantity of fertiliser used	$kg.ha^{-1}$	0
Planting density	$Cuttings.ha^{-1}$	10,000
Fence type		0
Fence perimeter length	m	N/A
MANAGEMENT		
Quantity Of herbicide used	$kg.ha^{-1}$	4.87
Quantity Of fertiliser used	$kg.ha^{-1}$	0
Year in which herbicide is applied first	yr.	3
Interval in herbicide application	yrs	3
Year in which fertiliser is applied first	yr.	0
Interval in fertiliser application	yrs	0
HARVESTING		
% of crop lost during harvesting	%	0
Distance travelled by tractor and trailer to unload harvest	km	1.5

Capacity of trailer	tonnes	8
TRANSPORT		
Distance between field and storage site	km	0
Vehicle capacity	T	0
STORAGE		
Moisture content of crop when harvested	%	46
Moisture content of fuel when ready for Conversion	%	25
Loss of mass during drying	%	3.54
Volume of drying facilities	m^3	764
% Heat taken from conversion used in storage	%	0
Storage/drying building size	m^3	800
Storage/drying building type	m^3	1
Volume per tonne of wood chip	m^3	0.045
CONVERSION		
Joules of electricity per tonne of fuel	J	0
Joules of heat per tonne of fuel	J	1.9×10^{10}
Conversion building size	m^3	135
Conversion building type	m^3	1
Size of conversion machines	m^3	100
% of heat from conversion used	%	100
% of electricity from conversion used	%	
% of the year that the conversion machine operates	%	58
% of required mass necessary to make it worth operating a machine	%	50
DECOMMISSIONING		
Quantity of herbicide used in decommissioning	$kg.ha^{-1}$	4.87
Lifespan of plantation	yrs	20

OPERATION	Est.	Man.	Harv.	Trans.	Stor.	Conv.	Decom.
Tractor + trailer	1	0	1	0	0	0	0
Tractor + sprayer	1	1	0	0	0	0	1
Tractor + fertiliser applicator	0	0	0	0	0	0	0
Tractor + plough	1	0	0	0	0	0	1
Tractor + harrow	1	0	0	0	0	0	0
Tractor + rotovator	0	0	0	0	0	0	0
Step planter	1	0	0	0	0	0	0
Harvesting *	0	0	0	0	0	0	0
Stand alone chipper	0	0	1	0	0	0	0
Storage handler	0	0	0	0	0	0	0
JCB	0	0	0	0	0	0	0
Transport▼	0	0	0	0	0	0	0
Transport by rail	0	0	0	0	0	0	0
Conversion**	0	0	0	0	0	2	0
Drying▼▼	0	0	0	0	1	0	0

*Loughry harvester = 1: Forage harvester = 2.

▼55 m^3 transporter (road) = 1: 80 m^3 transporter (road) = 2.

**30-kWe Gasifier = 1: Talbott boiler =2.

▼▼ Drying not using energy = 1: Drying = 2; Cooling and drying =3.

APPENDIX 3.

ANALYSIS OF WASTES PRODUCED DURING CHIPPED WILLOW GASIFIER TRIALS.

This appendix contains the results of analysis of wastes produced from wood chip trials with the 30 kWe gasifier system described in chapter 3. The results of this analysis are not conclusive but are included for there use in evaluating the system and future systems.

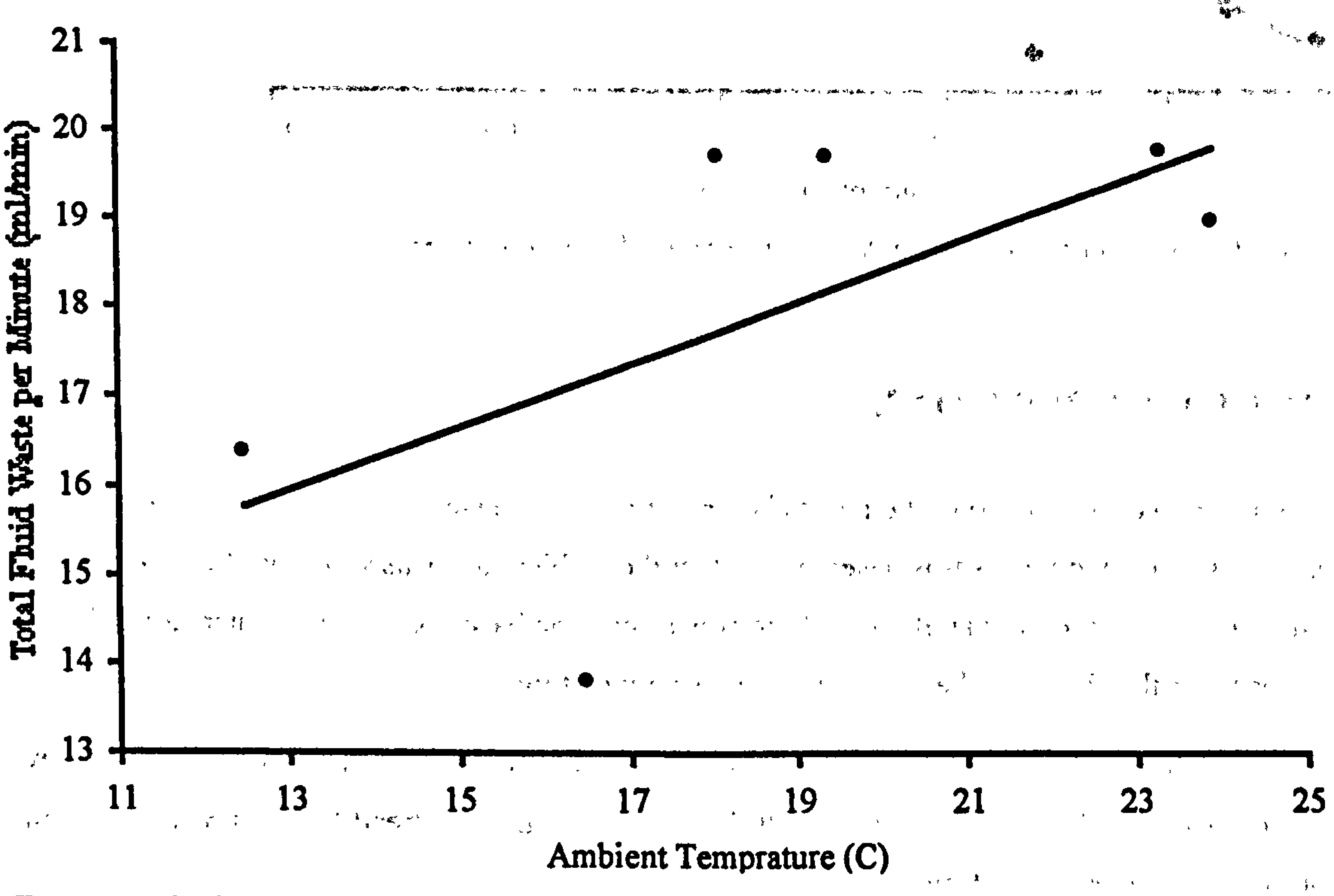

Figure 1. Fluid Waste Produced per minute against ambient temperature during run.

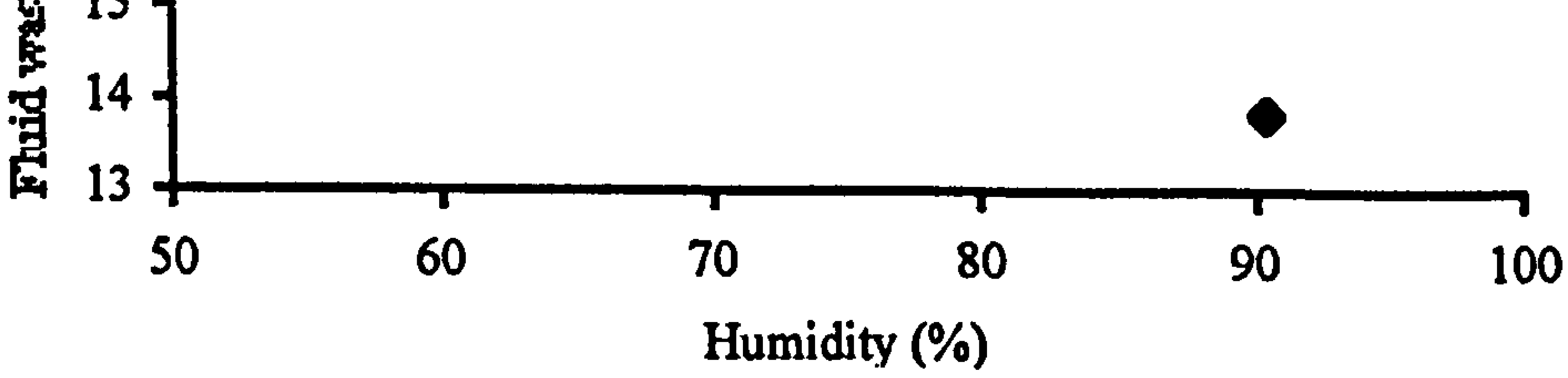

Figure 2. Fluid waste produced per minute against the humidity at experimental site

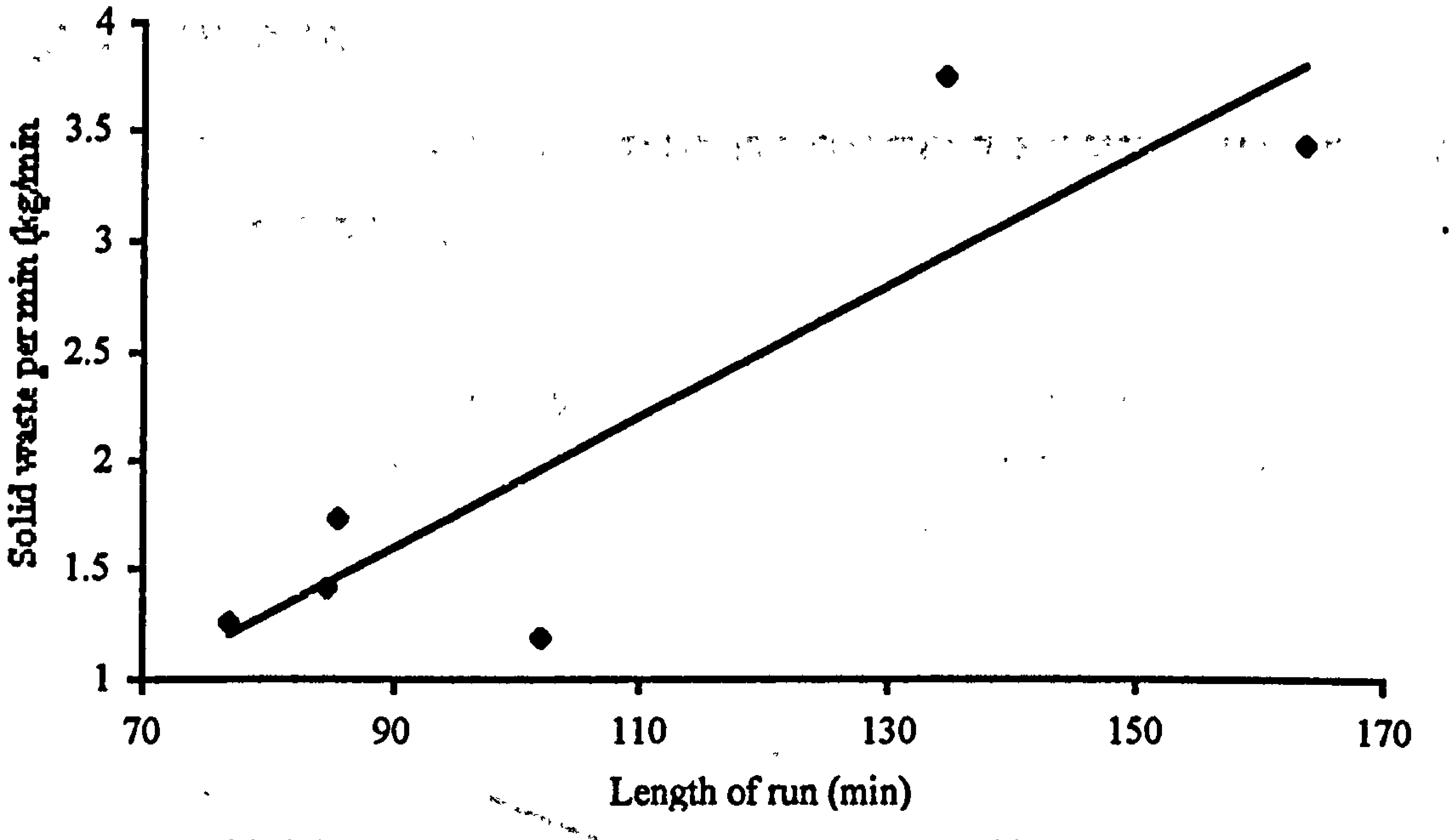

Figure 3. Total Solid Waste produced per minute against the total length of the run.

DISCUSSION OF FIGURES 1 TO 3.

It was hypothesised that the could be a correlation between the quantity of fluids produced and the atmospheric conditions. This hypothesis was based on the fact the ambient air is used to both fuel the process and as the cooling medium. Therefore variations in fluid waste could be based on either the increase fluids in the combustion process or the ability of the air to cool (i.e. its temperature).

The results of this analysis are shown in the graphs above. The lack of data points hampers any conclusions being drawn from this data. However in all three cases the general trend (show buy a liner fit in each graph) is of the direction expected from the hypothesis.

More experimental data could determine whether or not these trends can be substantiated.